Spectroscopic binaries

and high-order systems

in large surveys

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FED-tWIN

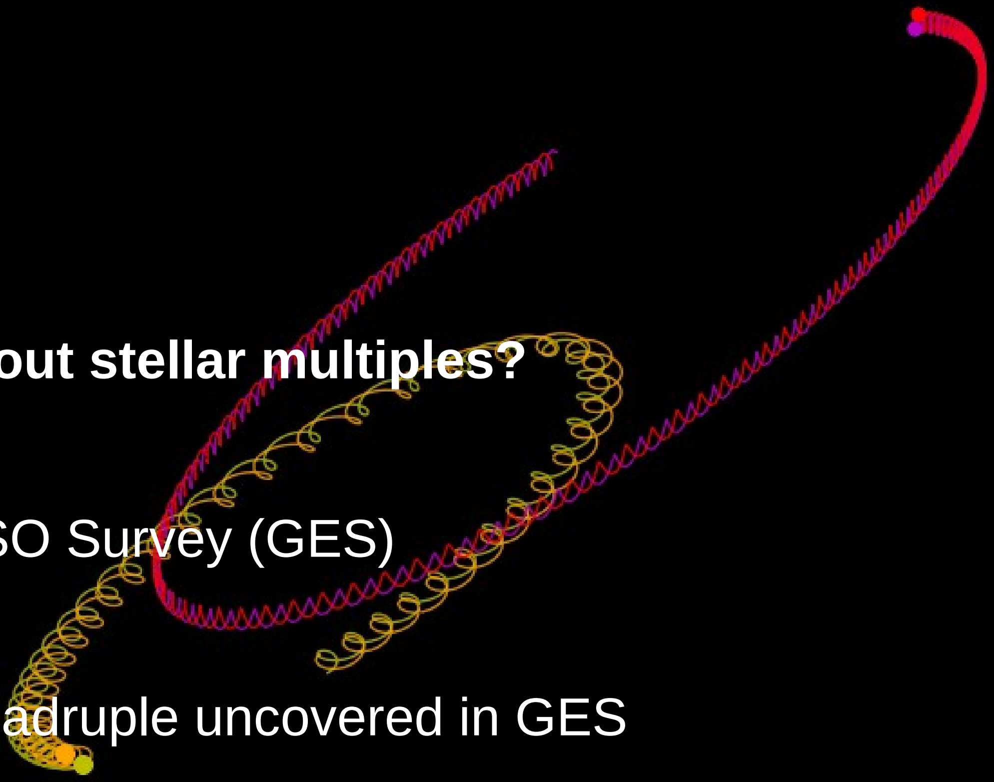
Outline

Introduction: why should we care about stellar multiples?

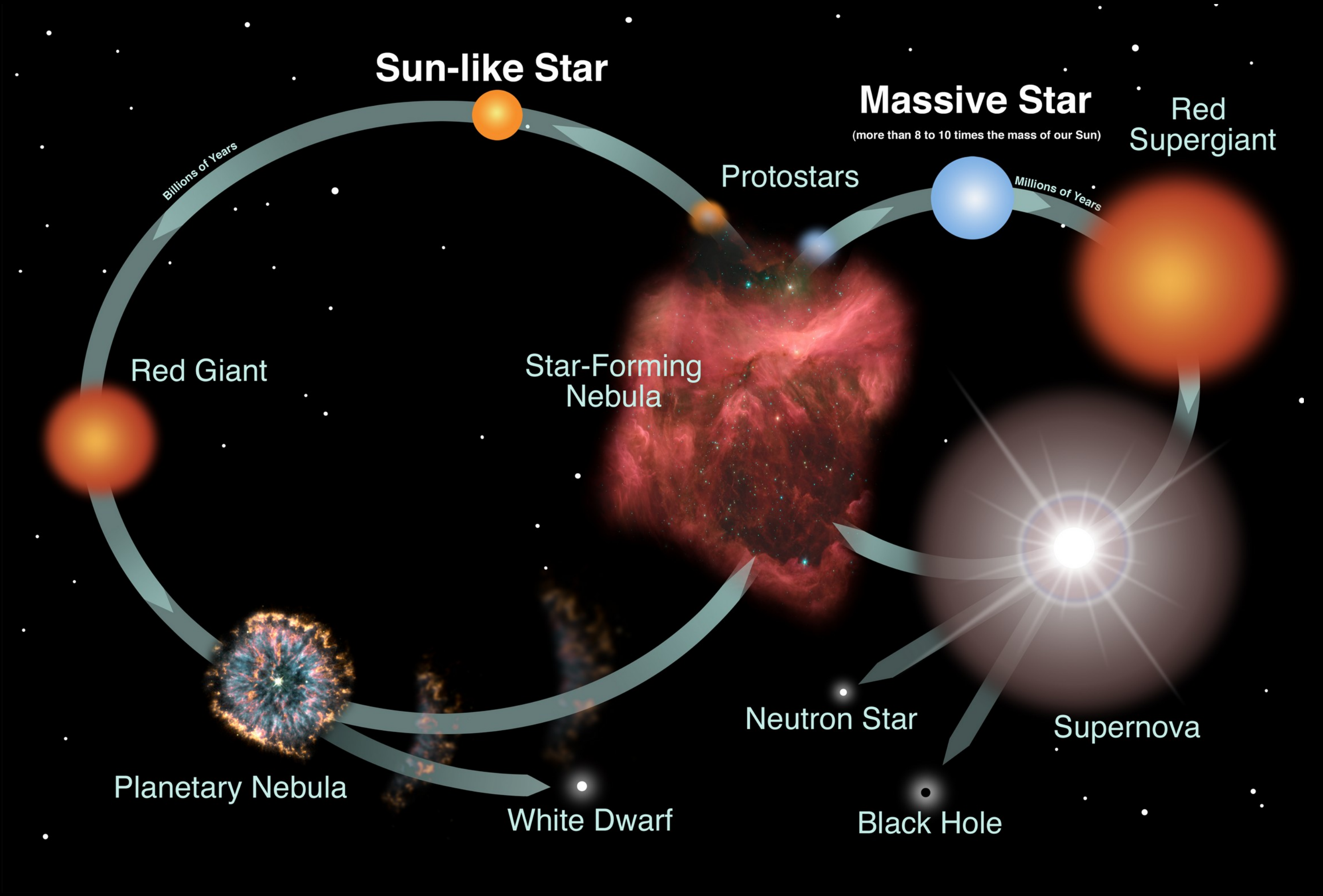
I. Spectroscopic binaries in the Gaia-ESO Survey (GES)

II. HD 74438: a young spectroscopic quadruple uncovered in GES

III. Spectroscopic binaries in other surveys

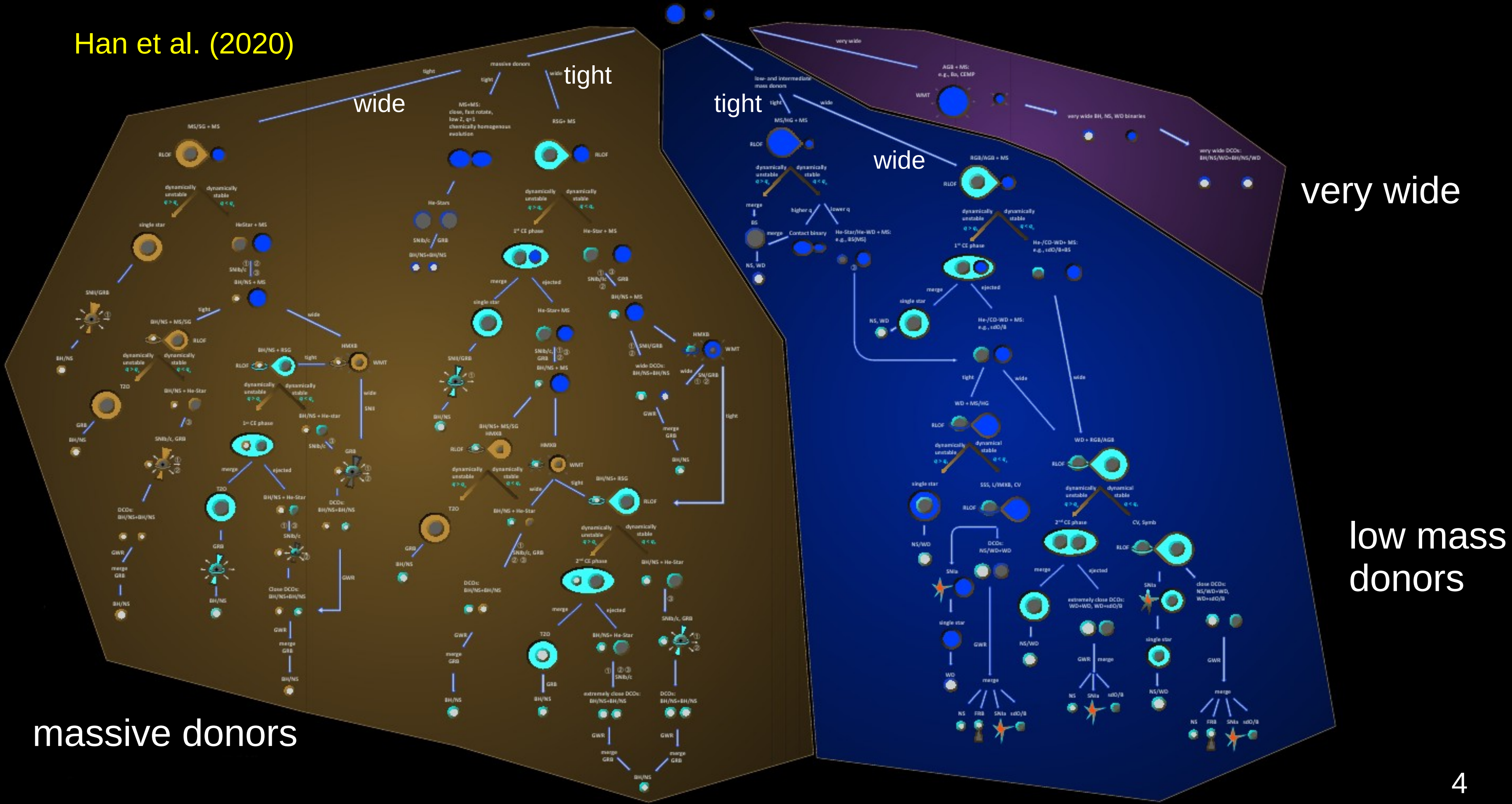


Introduction: single star evolution

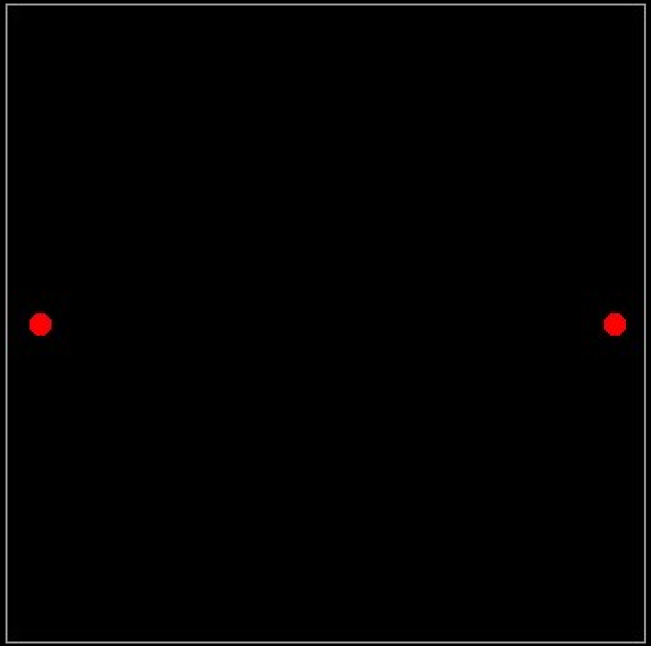


Introduction: binary star evolution

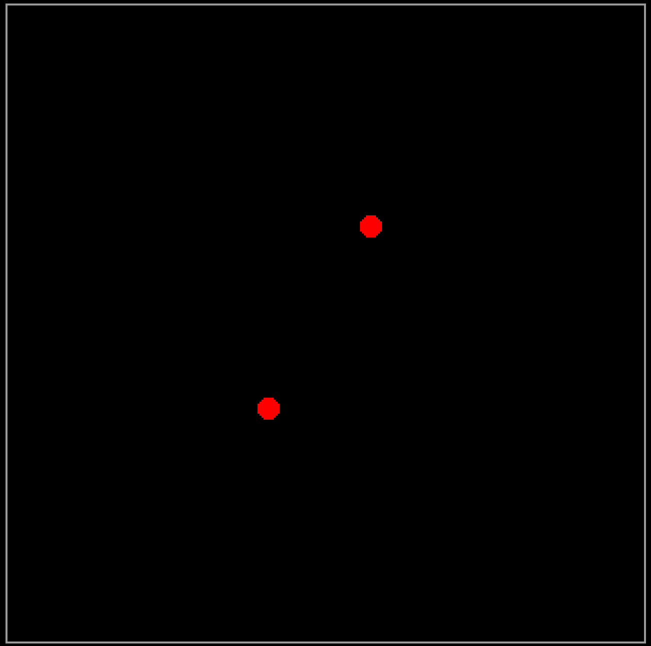
Han et al. (2020)



Introduction: multiple stars architecture

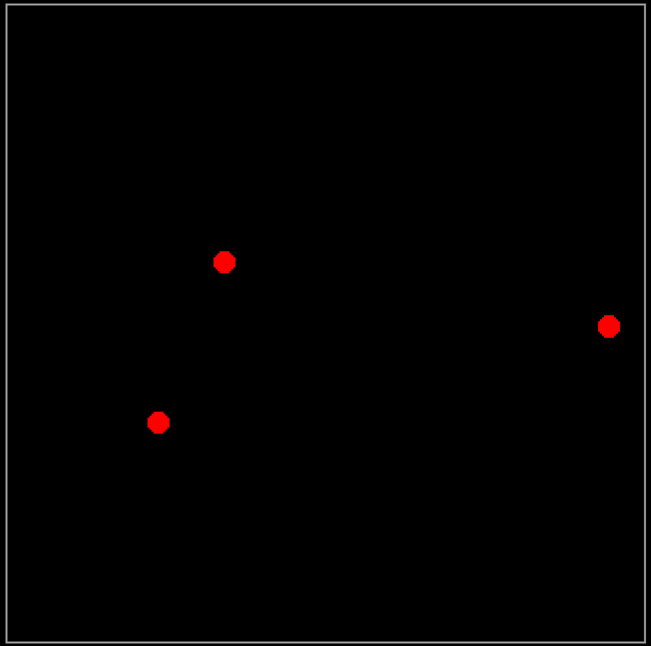


Circular binary system

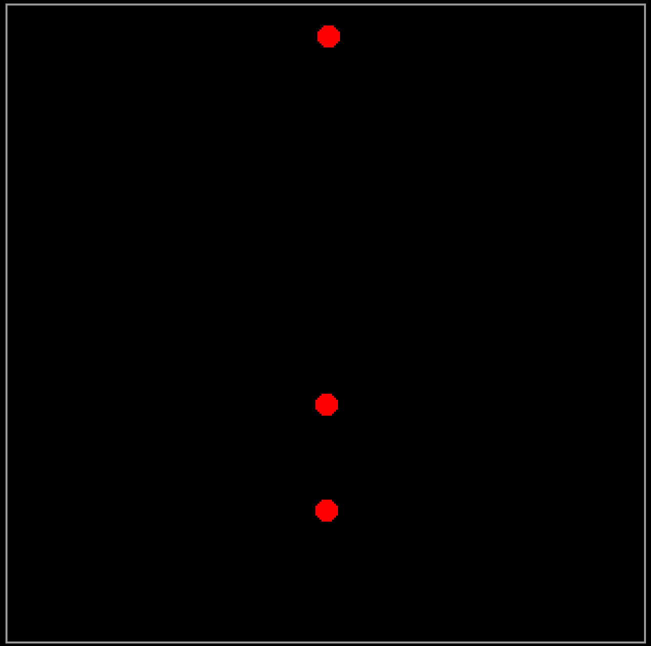


Elliptical binary system

Introduction: multiple stars architecture

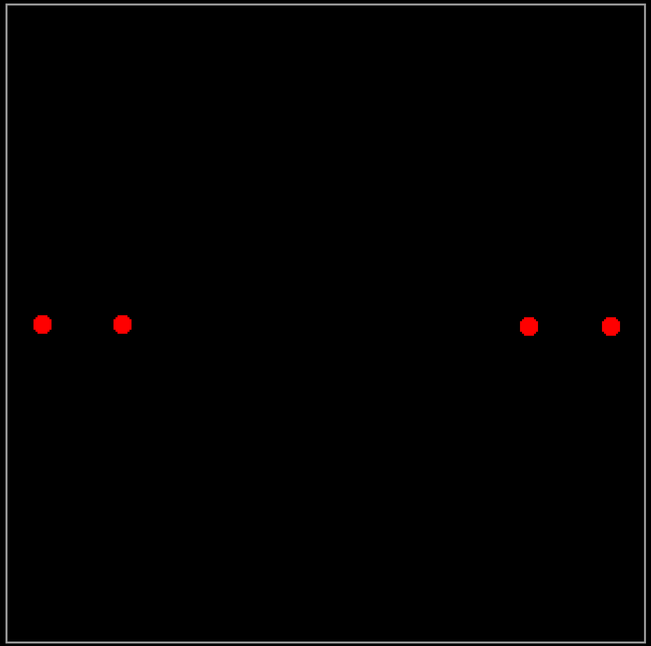


Triple system (unstable)
1+1+1

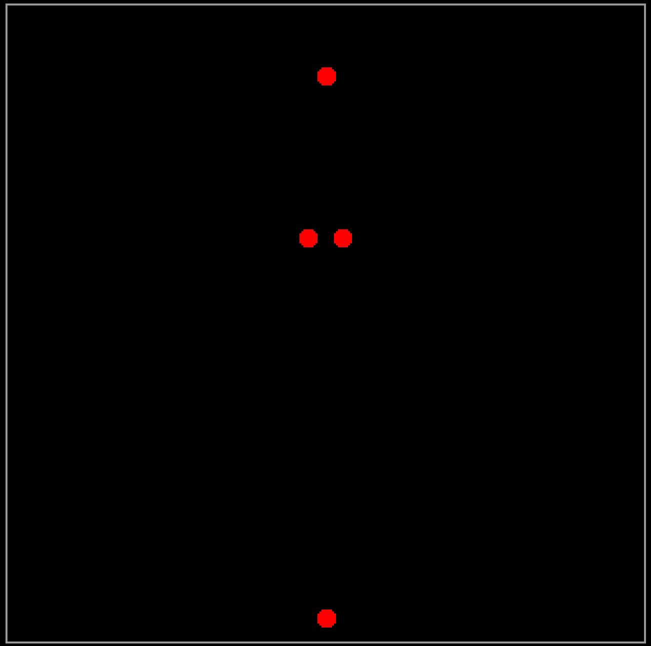


Hierarchical triple system
2+1

Introduction: multiple stars architecture



Quadruple system
2+2
2 hierarchical levels



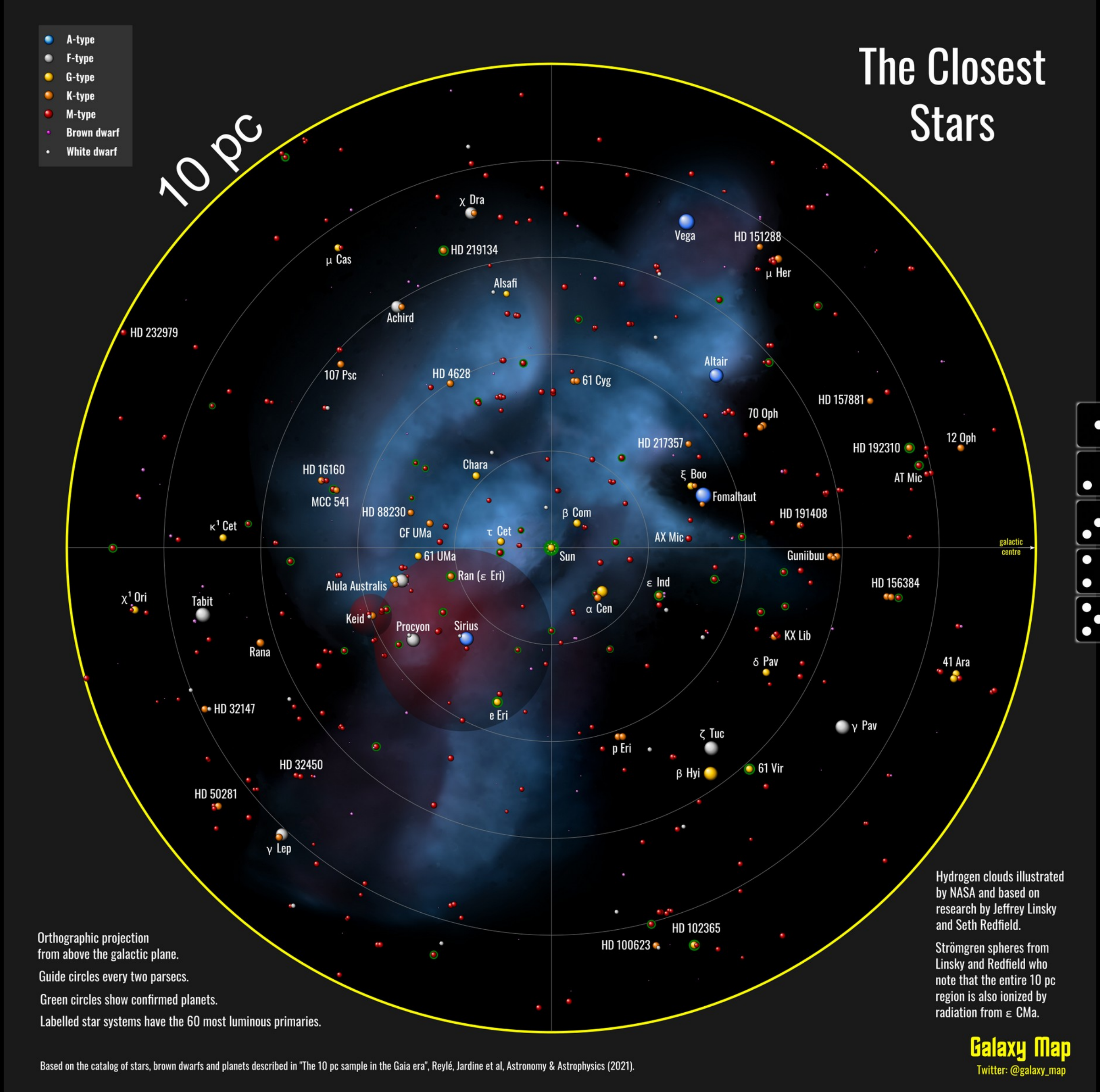
Quadruple system
3+1
3 hierarchical levels

Census: 541

317 stars

0	O
0	B
4	A
8	F
18	G
38	K
249	M

86 brown dwarfs
77 exoplanets
20 white dwarfs
41 N/A



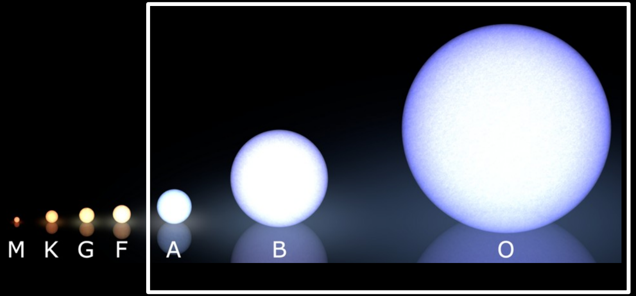
Stellar Systems: 339

Single:	245
Binary:	70
Triple:	19
Quadruple:	3
Quintuples:	2

Quadruples: GJ 570, μ Her & GJ 867
Quintuples: ξ UMa & HD 152751

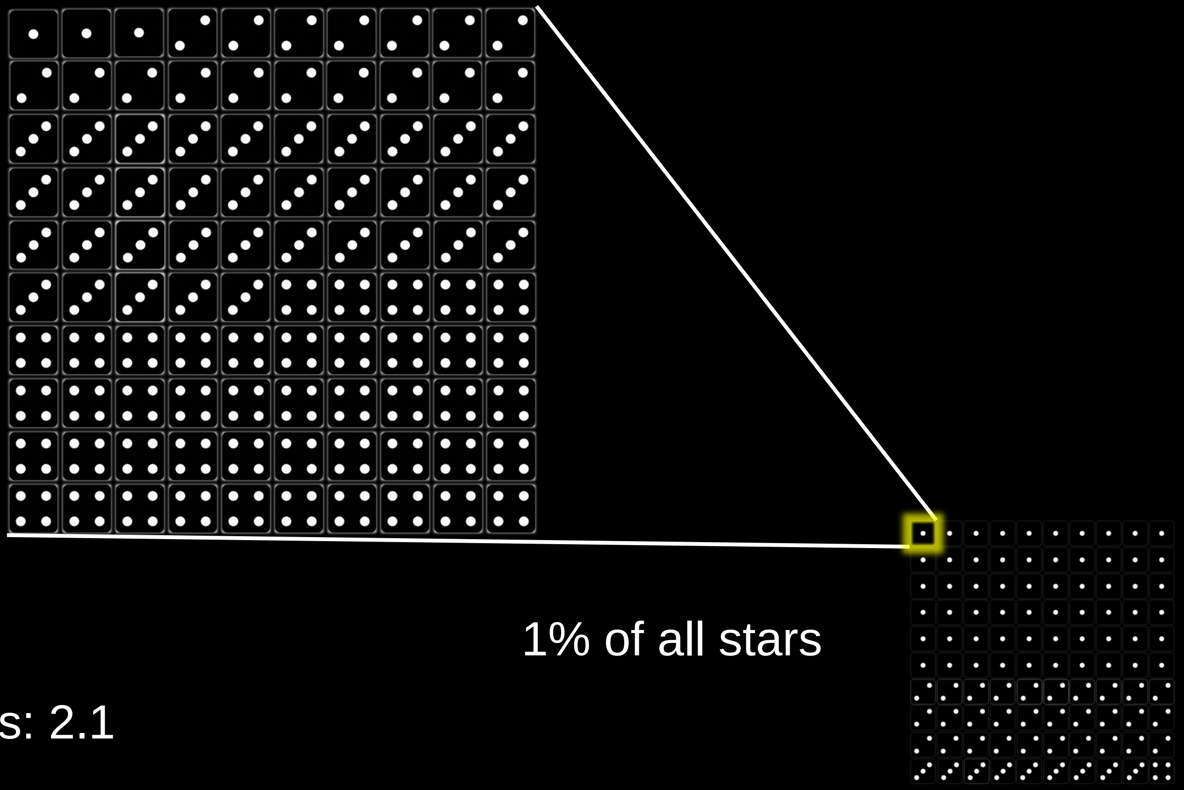
Reylé et al. (2021)

Introduction: multiplicity statistics in early-type stars



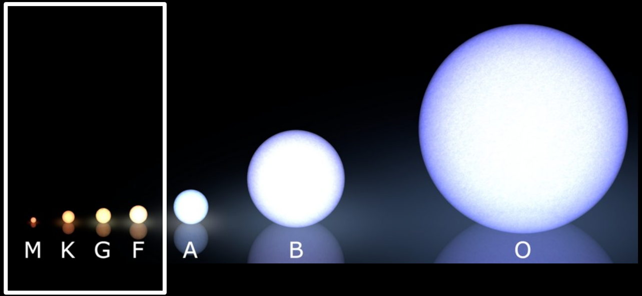
Single:	3%
Binary:	17%
Triple:	35%
Quadruple:	45%

Multiplicity fraction: 97%



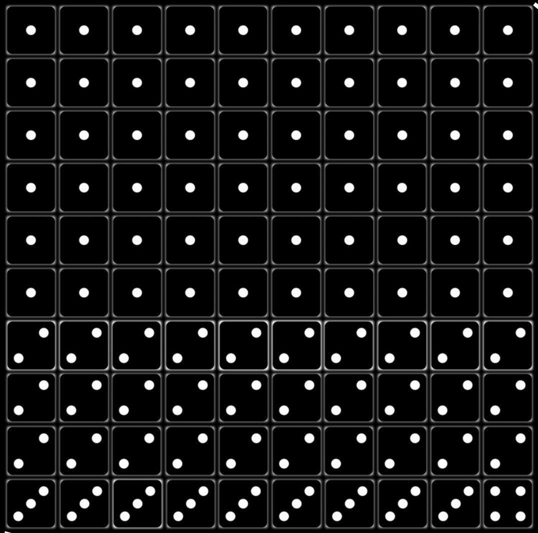
Mean number of companions: 2.1

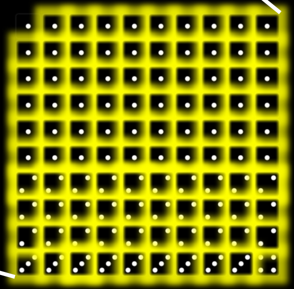
Introduction: multiplicity statistics in late-type stars



Single: 60%
Binary: 30%
Triple: 9%
Quadruple: 1%

Multiplicity fraction: 40%

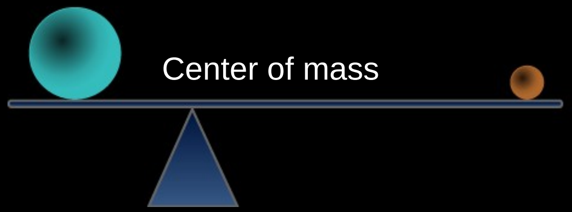




99% of all stars

Mean number of companions: 0.5

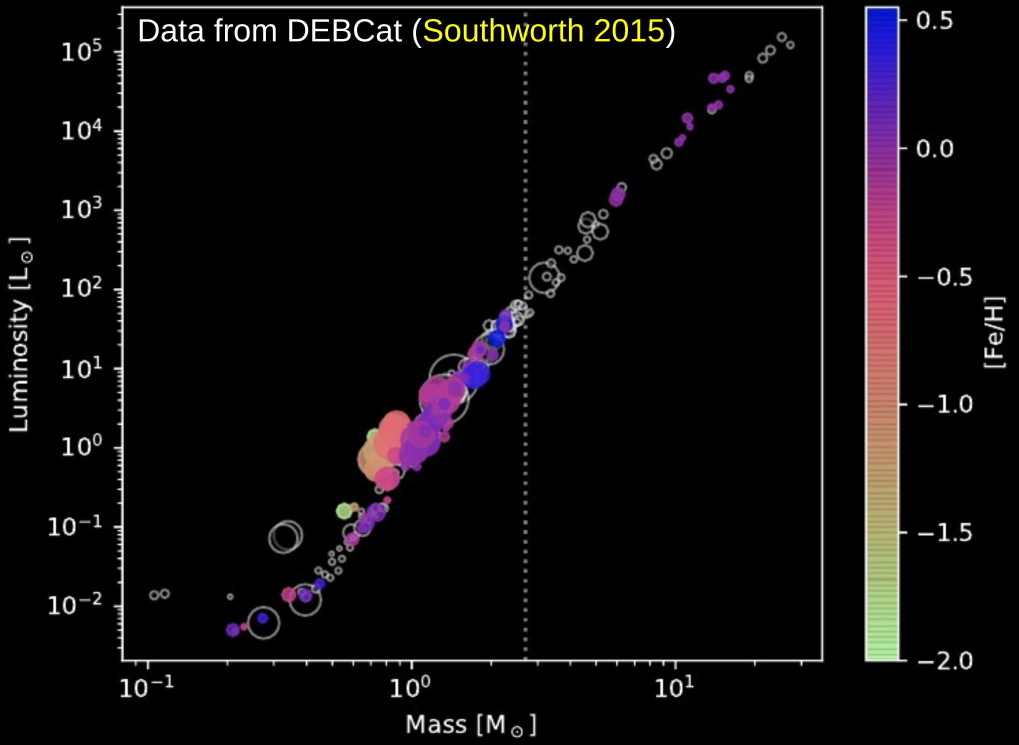
Introduction: why do we care about stellar multiples?
1. Benchmarking



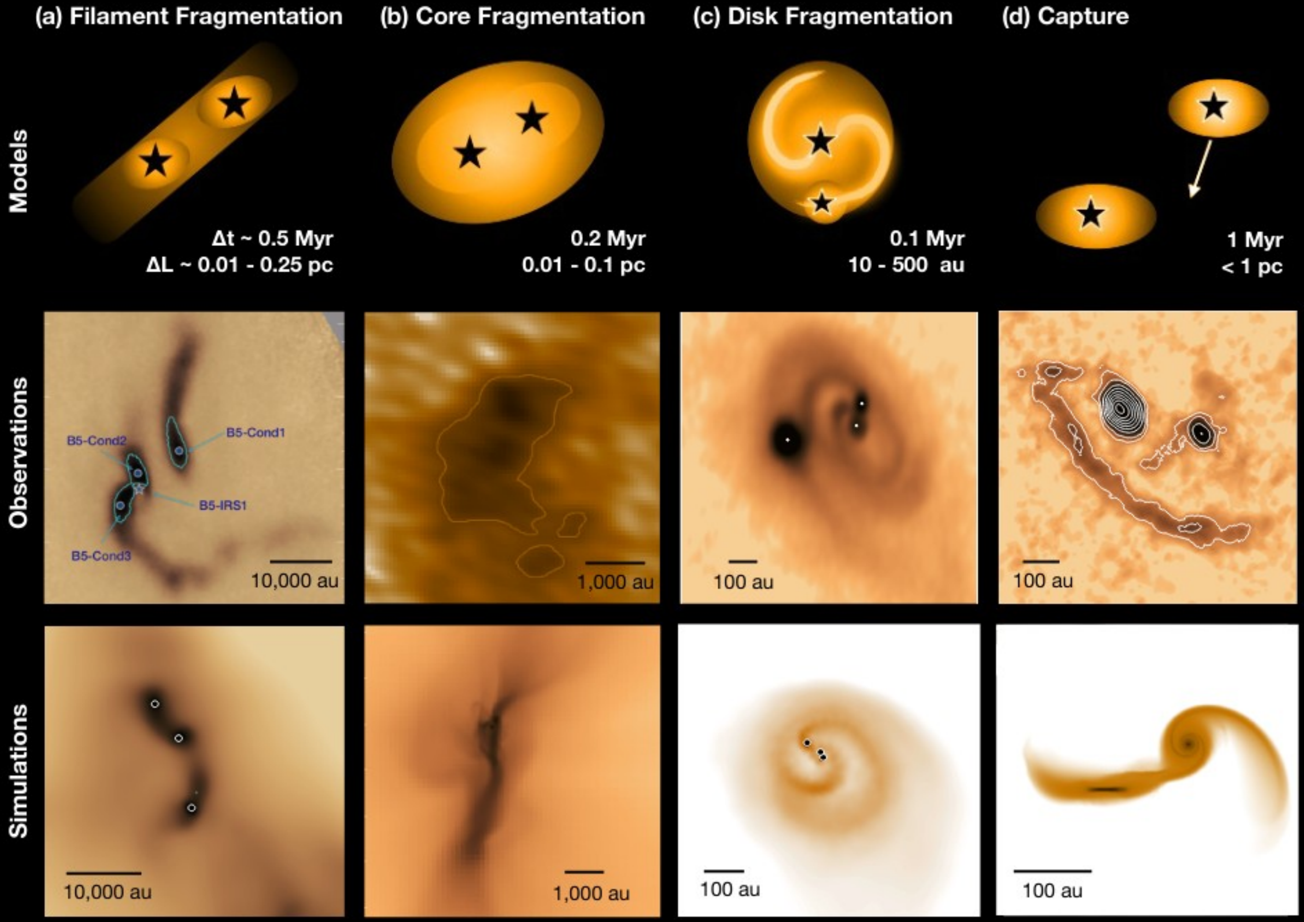
Benchmarks for fundamental stellar parameters like mass, radius & luminosity as well as the stellar parallax

Detached binary stars evolve as single stars:

- Cornerstones on which single-star evolutionary models are anchored
- Provide precise mass-radius and mass-luminosity calibration scales



Introduction: why do we care about stellar multiples?
2. Stellar formation

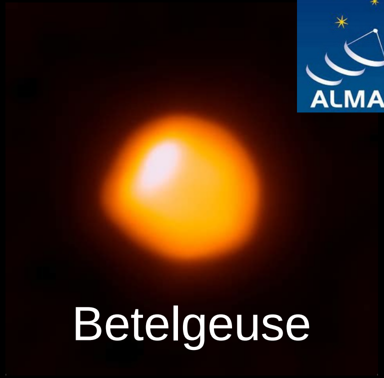


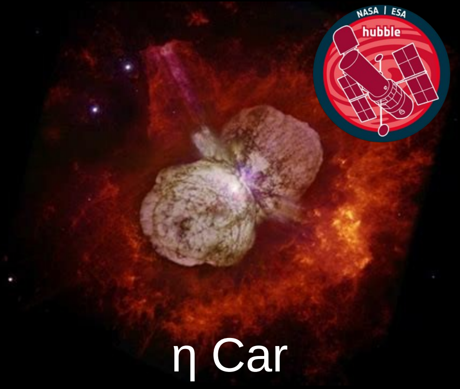
- Elementary mechanisms
  - Filament/core/disk fragmentation
  - Dynamical interaction
- Observations
  - B5 in Perseus (Pineda et al. 2015)
  - SM1N in Ophiuchus (Kirk et al. 2017)
  - L1448 IRS3B in Perseus (Reynolds et al. 2021)
  - RW Aur (Rodriguez et al. 2018)
- Simulations
  - Guszejnov et al. (2021)
  - Offner et al. (2016)
  - Bate (2018)
  - Muñoz et al. (2015)

Offner+ (2022)

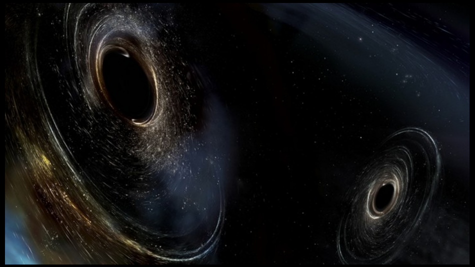
Introduction: why do we care about stellar multiples?
3. Stellar evolution

Chandra/Hubble/Spitzer

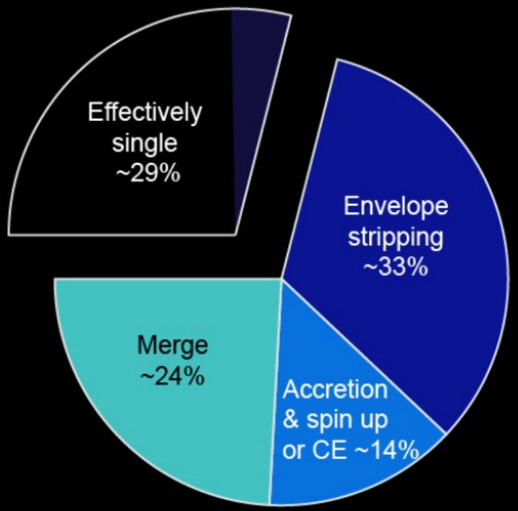




GW 150914

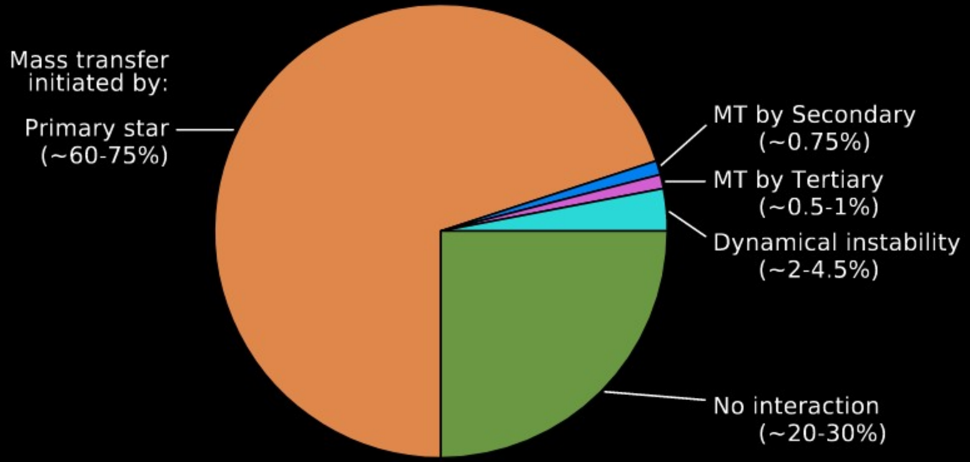


Introduction: why do we care about stellar multiples?
3. Stellar evolution



O-type binaries

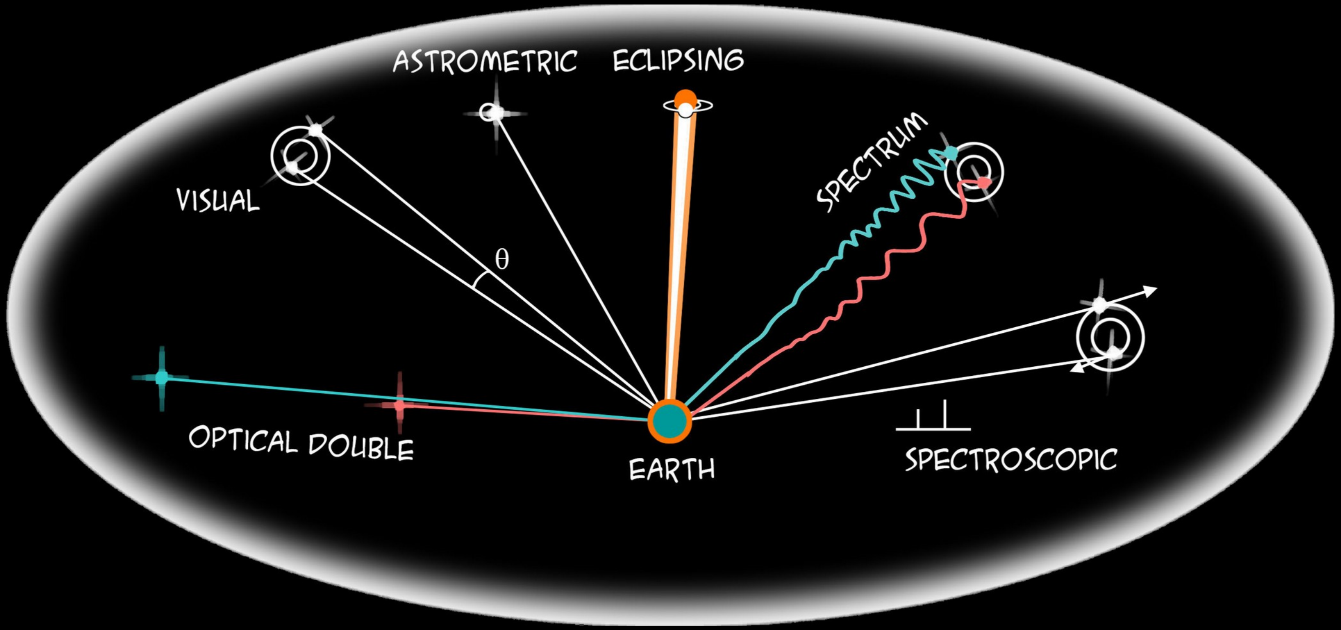
Sana+ (2012)

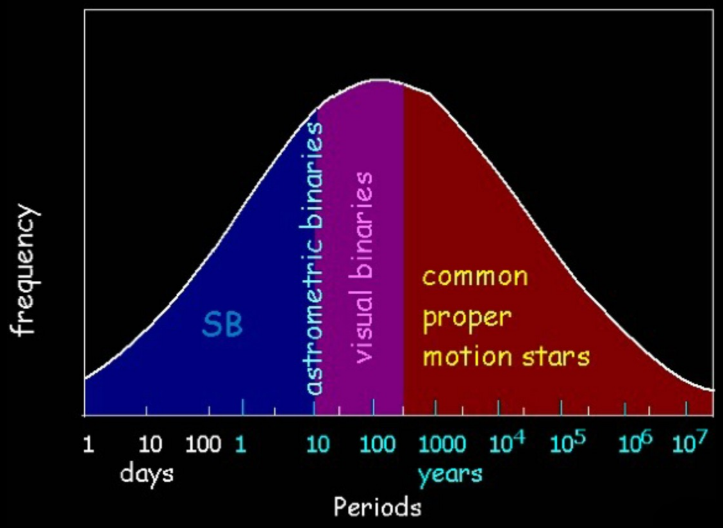


1-7.5 $M_\odot$ primaries in triples

Toonen+ (2020)

Introduction: How do we detect stellar multiples?

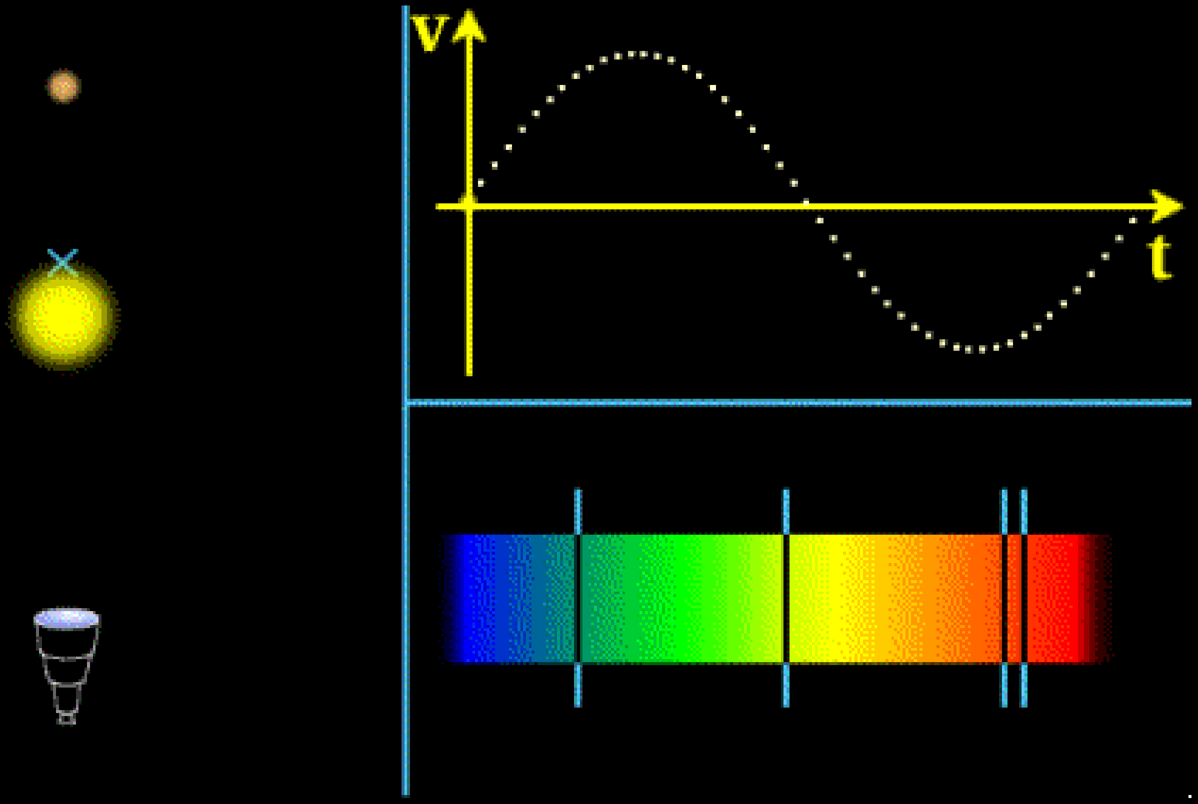




log (P[d]) ~ 5 ⇔ 270 y, σ ~ 2.5

Visual/astrometric/interferometric binaries = AB
Eclipsing/photometric binaries = EB
Spectroscopic binaries = SB

Introduction: the method of radial velocities (RV)



Radial velocity:
$v = \Delta\lambda / \lambda_0 \; c$

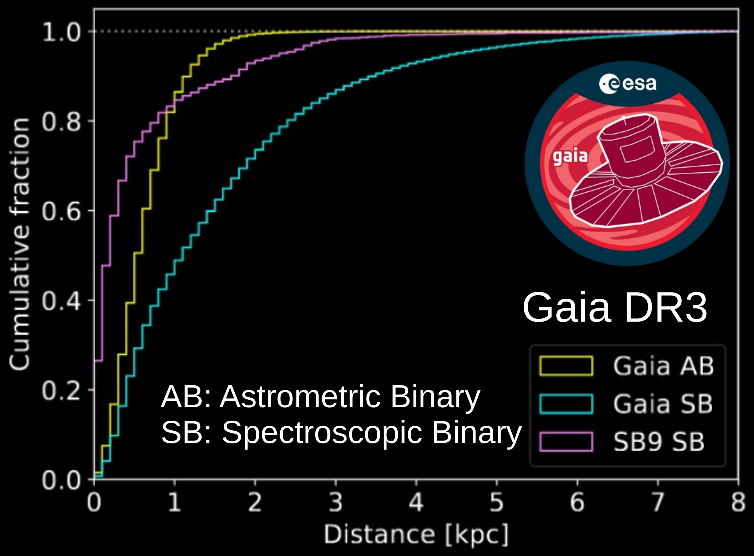
$\Delta\lambda$: the Doppler shift

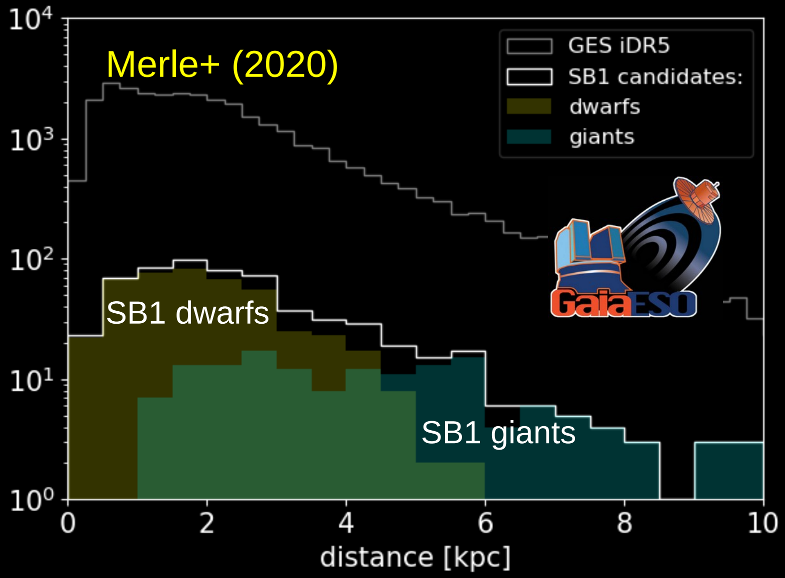
λ_0 : the rest wavelength

c: speed of light

Introduction: why spectroscopic binaries (SB)?

Van der swaelmen+, in prep.





Dimitri Pourbaix

1969 - 2021

The SB9 catalogue

- Their detection is insensitive to the distance
- They probe the shorter part of the period distribution
- Several SB catalogues attached to various ground-based surveys (RAVE, APOGEE, etc.)
- The Ninth Catalogue of Spectroscopic Binary Orbits (**SB9**, Pourbaix+ 2004): last release in March 2021 with ~ 4000 orbits

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I. The Gaia-ESO Survey (GES)

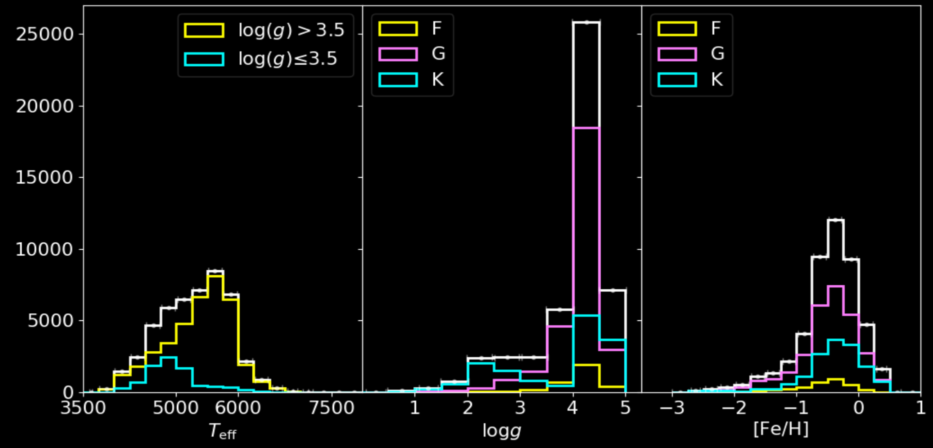
Large spectroscopic surveys with GIRAFFE (*R* ~20 000) and UVES (R = 47 000) spectrographs

Study of the formation history of stellar populations of the Milky-Way:
> 100 000 stars in bulge, discs, halo and stellar clusters (Gilmore et al. 2022, Randich et al. 2022)

GES DR5.1 final release in July 2023: https://www.eso.org/qi/catalogQuery/index/393

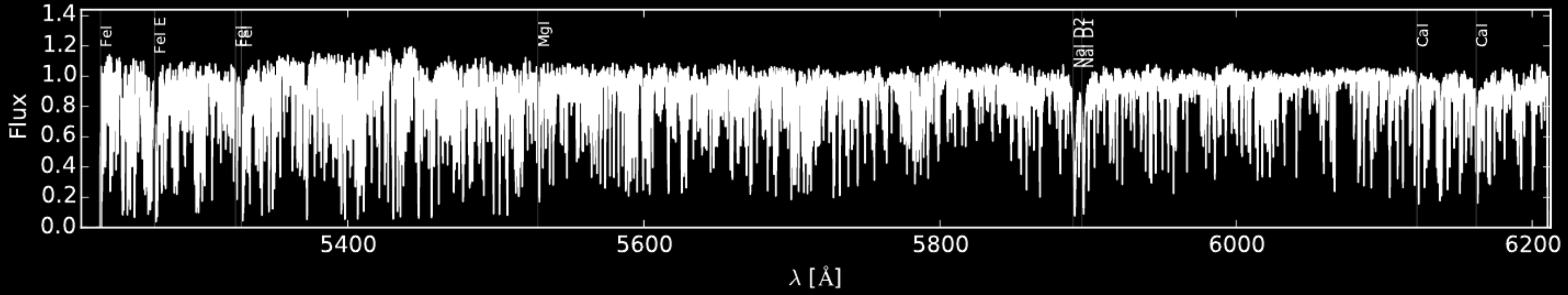
Observing strategy not adapted to the detection of binaries but:

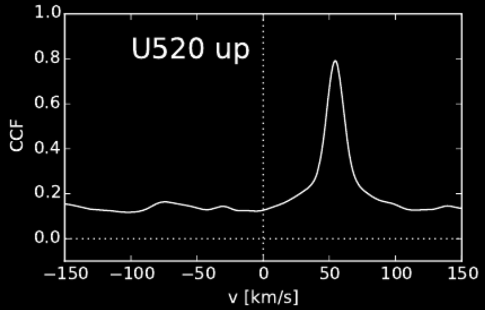
- Merle, Van Eck, Jorissen et al. (2017): ~ 340 SB2, ~10 SB3 & 1 SB4
- Merle, Van der Swaelmen, Van Eck et al. (2020): ~800 SB1
- Van der Swaelmen, Merle, Van Eck et al. (accepted) > 430 SB2



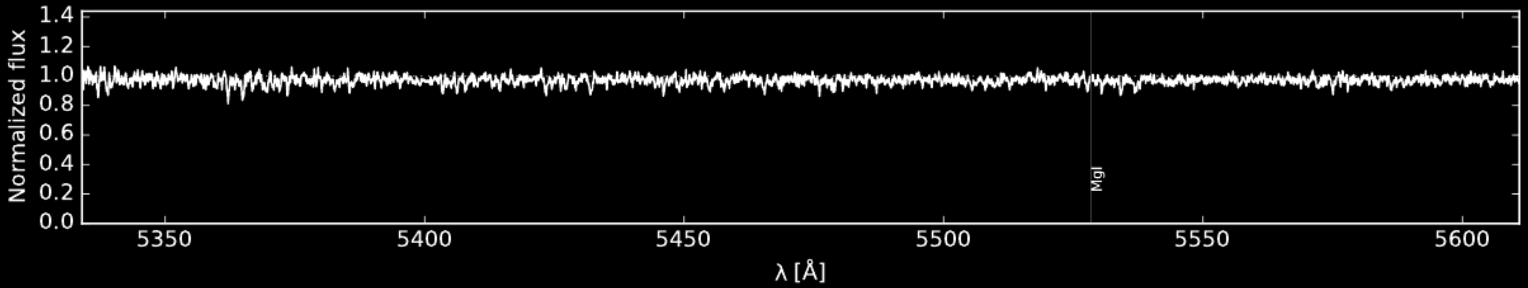
I. Measuring RV with Cross-Correlation Function (CCF)

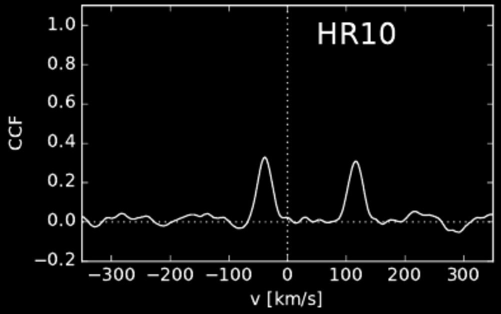
CCF used to measure RV by combining information of thousands lines:



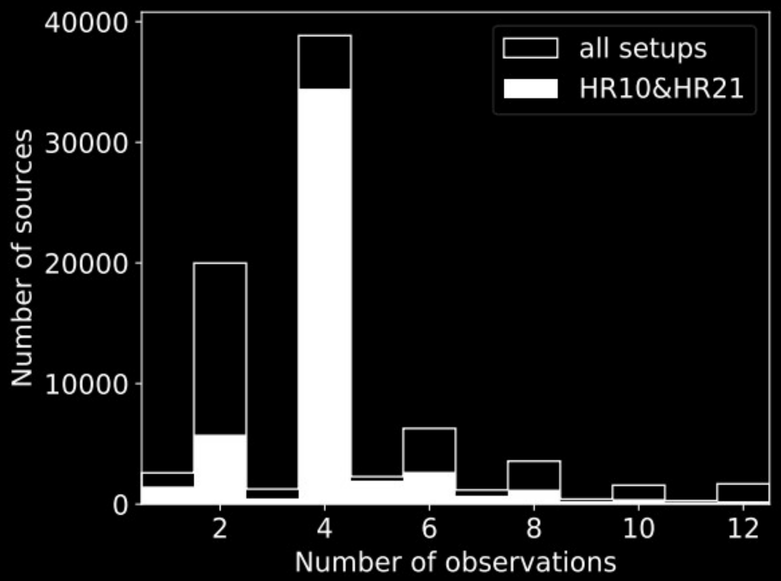


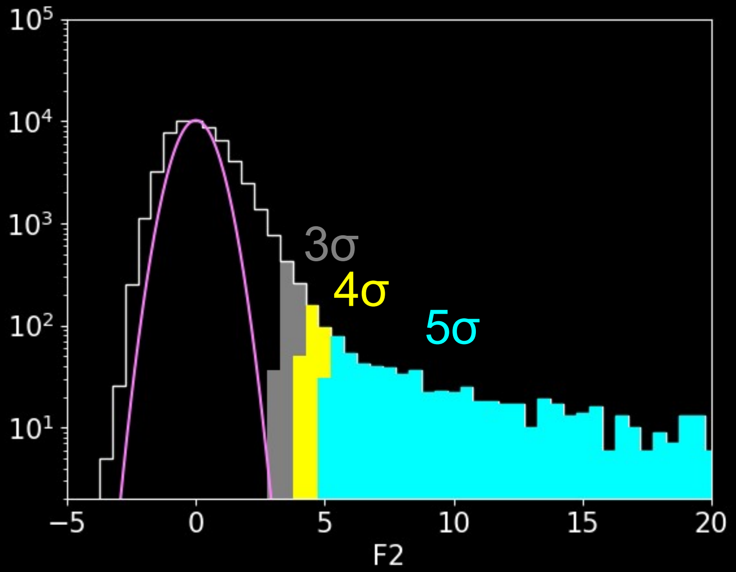
Binary stars showing composite spectrum are easily detected with their CCFs





I. How to detect SB with one visible component (SB1)?





60 000 stars
At least N = 2 exposures
S/N ⩾ 3

Statistical χ²-test: $$\chi^2_{N-1} = \sum_{i=1}^{N} \left(\frac{v_i - \bar{v}}{e_i} \right)^2$$

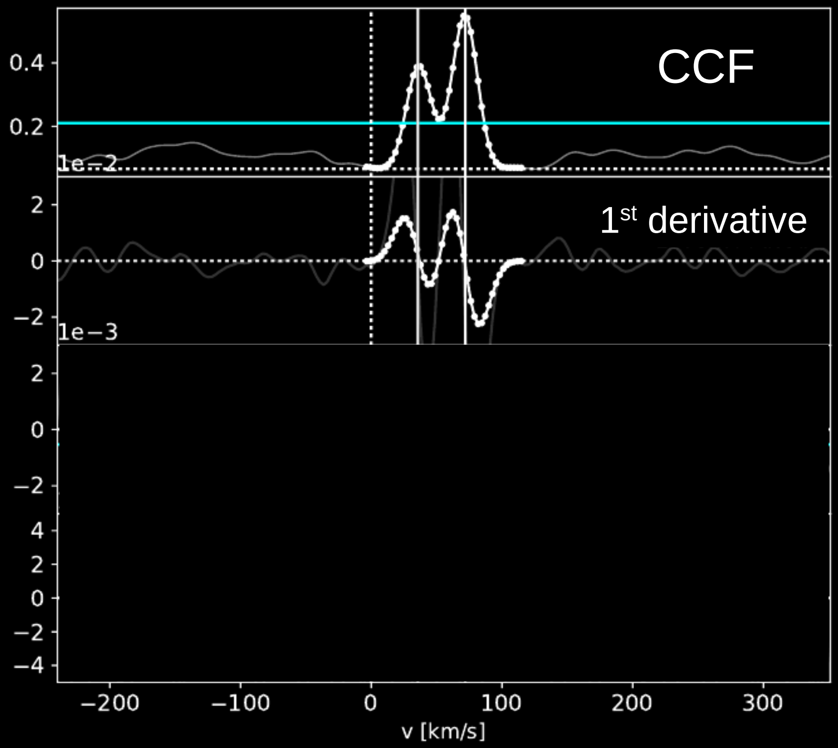
F2 statistics (Wilson&Hilferti 1931):

$$F2(\chi^2, N) = \sqrt{\frac{9(N-1)}{2}} \left[\left(\frac{\chi^2}{N-1} \right)^{1/3} + \frac{2}{9(N-1)} - 1 \right]$$

χ^2_{N-1} → **F2**: $\mathcal{N}$**(0, 1)** independent of ***N***

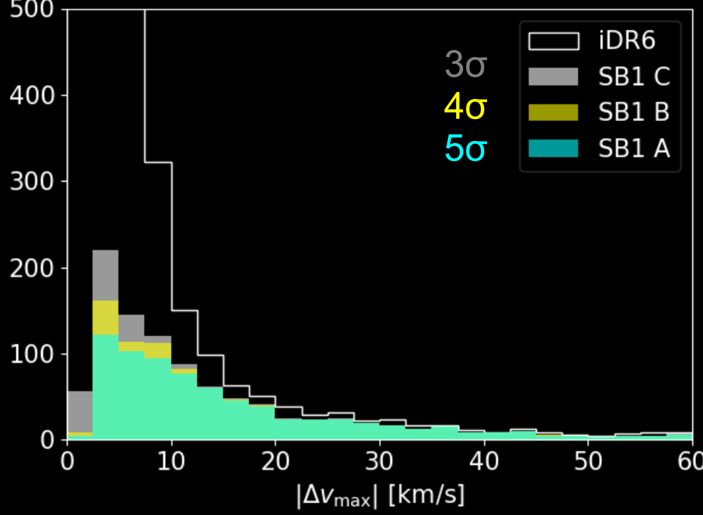
I. How to detect SB with *n* visible components (SB*n*, *n* ⩾ 2)?

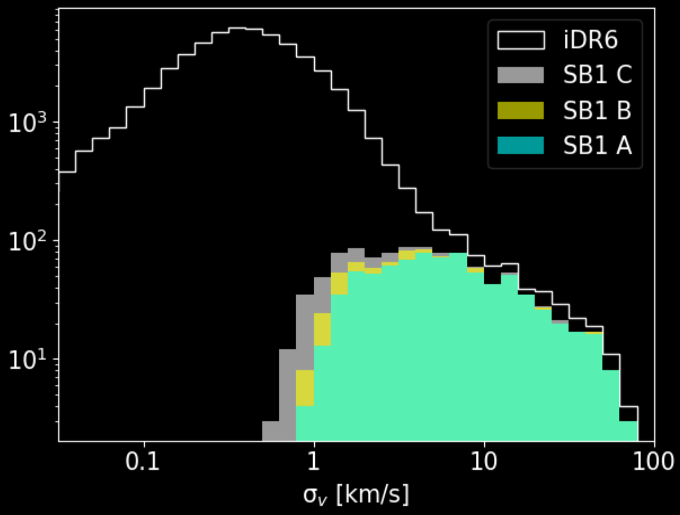
- Developed and used in Merle et al. (2017)
- Also used in: Kravchenko et al. (2019) – Betelgeuse, Traven et al. (2020) – GALAH, Merle et al. (2022) – SB4
- Under implementation in the 4MOST galactic pipeline

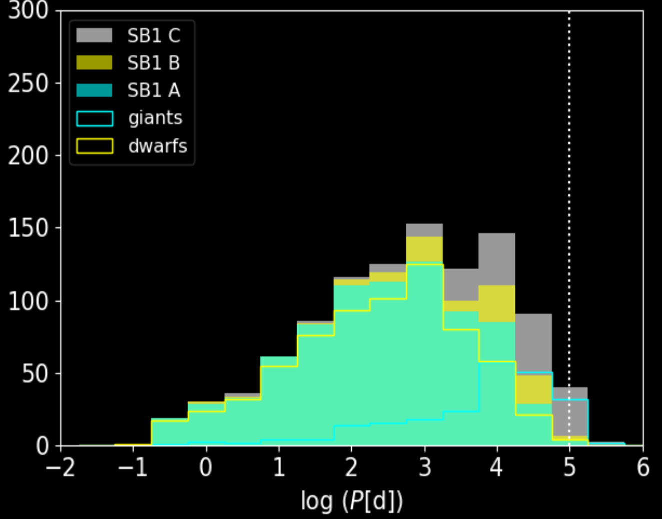


I. Statistical properties of SB1 in the GES

Merle, Van Eck, Jorissen et al. (2020), Merle+ (in prep.)







$$P = 9.650 \times 10^4 \frac{1}{K^3} \frac{\sin^3 i}{(1 - e^2)^{3/2}}$$

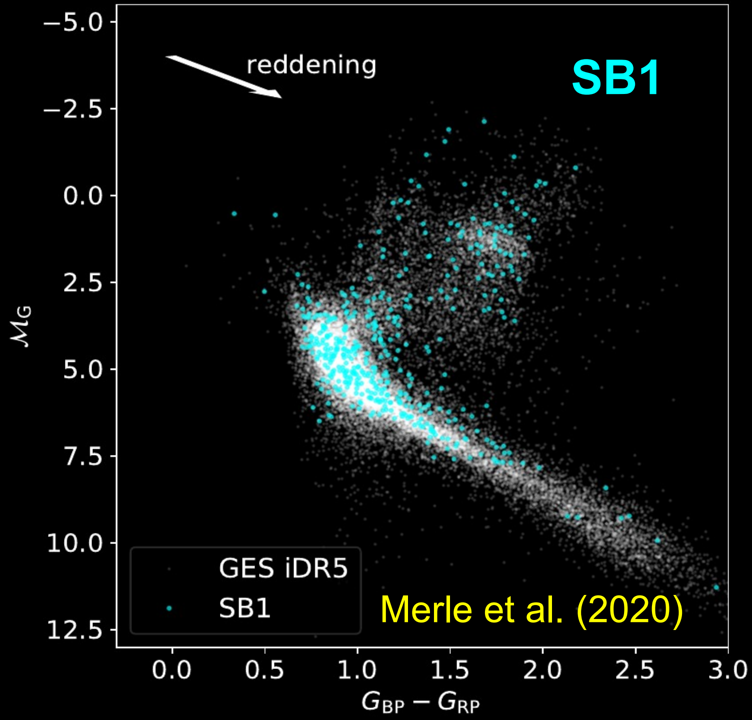
- RV amplitude estimator: $K = \sqrt{2}\,\sigma_v$
- mass of the primary: $M = 1\ M_\odot$
- mass ratio $q = 0.25$
- random inclination on the sky: $i = 68°$
- median eccentricity in the SB9: $e = 0.2$

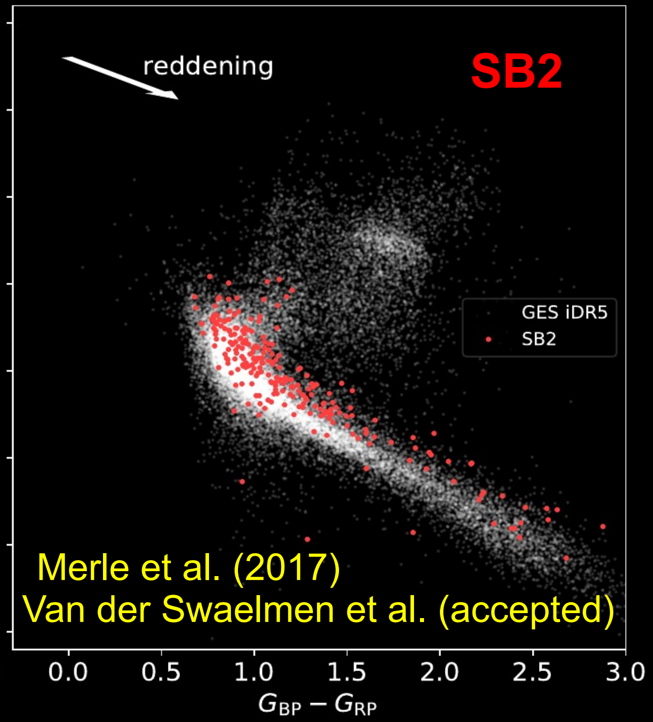
According to Moe & Di Stefano (2017):

- 30% ± 10% of SB1s contain compact remnant companions
  - Sirius-like binaries with hot white dwarfs
  - Barium stars
- 70% ± 10% of SB1s have M dwarfs secondaries

I. Statistical properties of SB1 & SB2 in the (GES)

Parallaxes and G, BP, RP photometry from Gaia DR2:
Locii in the color-absolute magnitude diagram of **SB1** and **SB2**





Monte Carlo simulations to estimate the detection efficiency of our methods using the SB9 (Pourbaix+ 2004-2014)

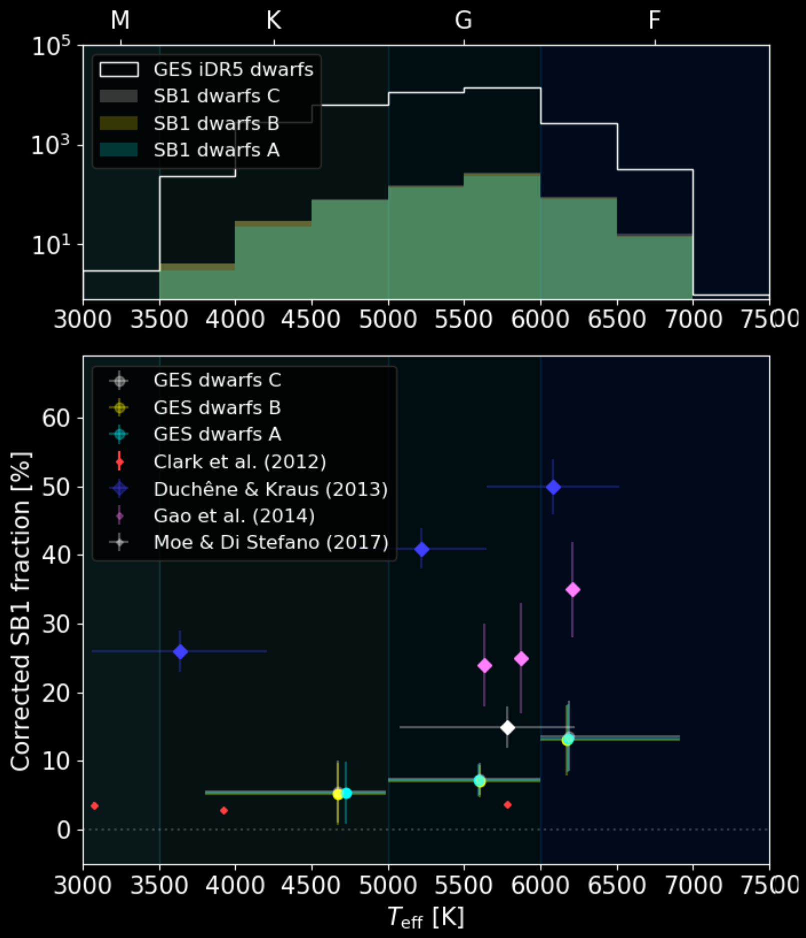
SB1 detection efficiency: 19%
SB2 detection efficiency: 62%

Total GES SB frequency: 12%

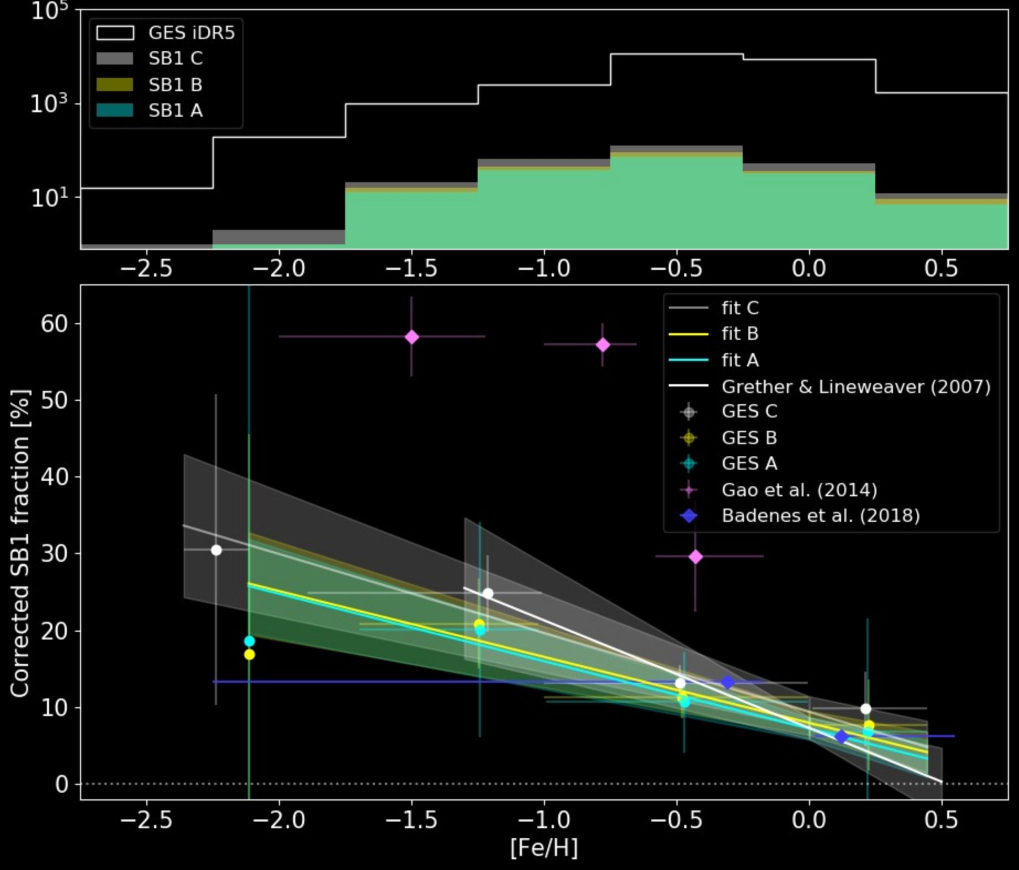
SB1 frequency: 9.8 ± 1.8%
SB2 frequency: ~ 2%

Close binary fraction from
Moe & Di Stefano (2017): 15 ± 3%

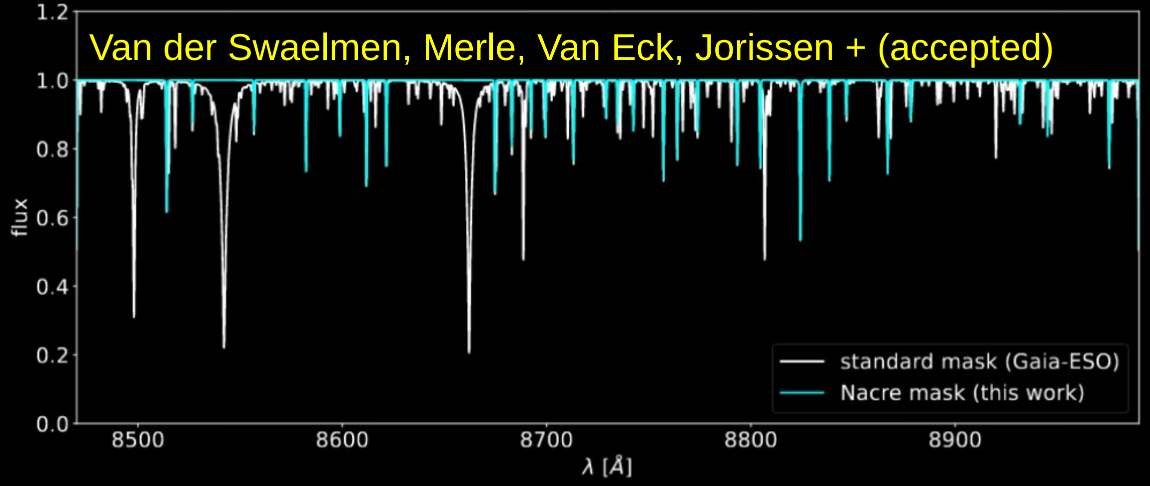
I. Statistical properties of SB1 & SB2 in the (GES)

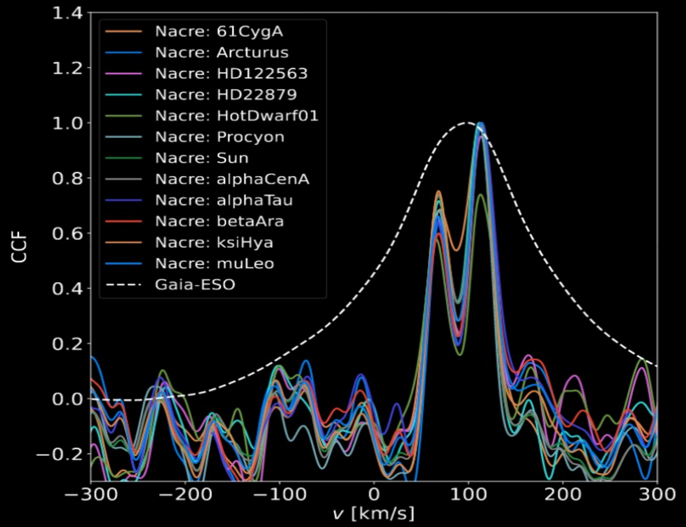


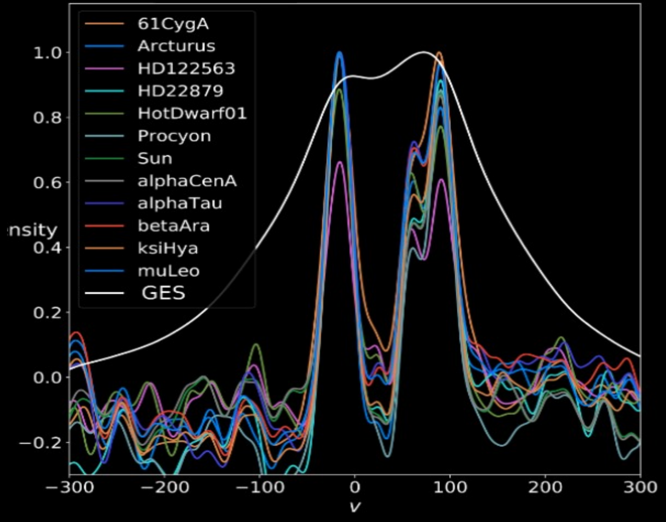
Merle, Van der Swaelmen, Van eck, Jorissen+ (2020)



I. Improvement of binary detection







New sets of CCFs with optimized masks for HR10 & HR21

NArrow Cross-Correlation Experiment (NACRE):

- Template stars among FGK benchmark stars (Jofré+ 2015)
- Selection of at least 10 weak and unblended lines
- Masking the Ca II IR triplet, H lines and tellurics at the red end

Sensitivity in setup HR21 increases at the level of HR10:

- Decrease of the Δv_{min} from ~60 to 25 km/s
- Increase of the number of SB2 and SB3 by 1/3

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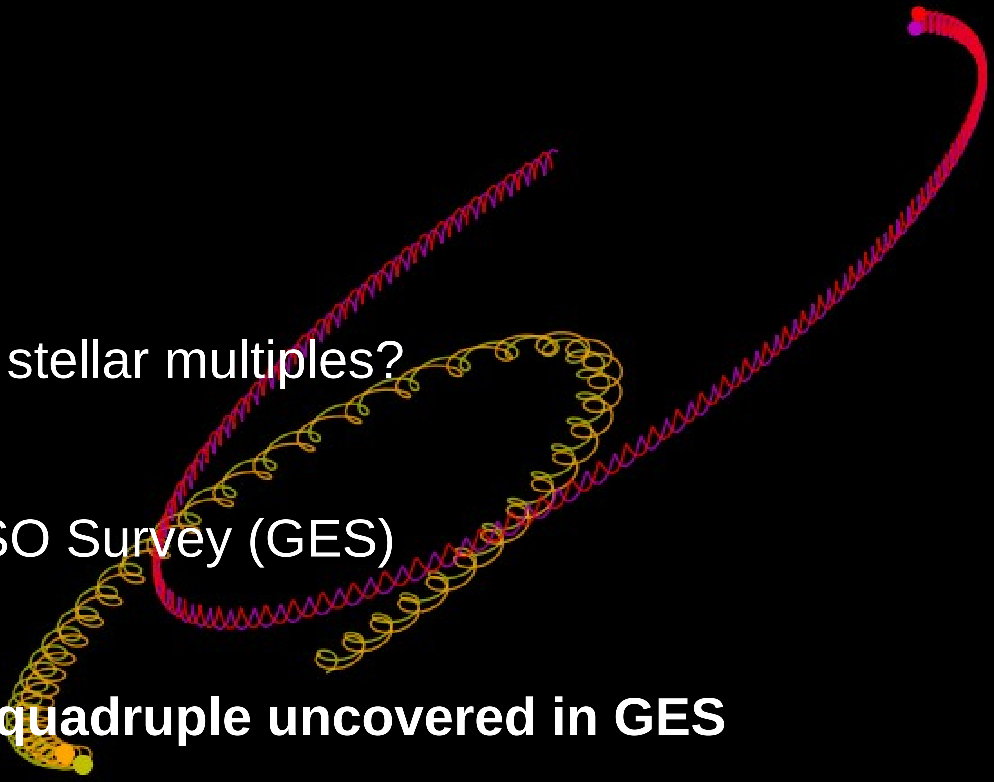
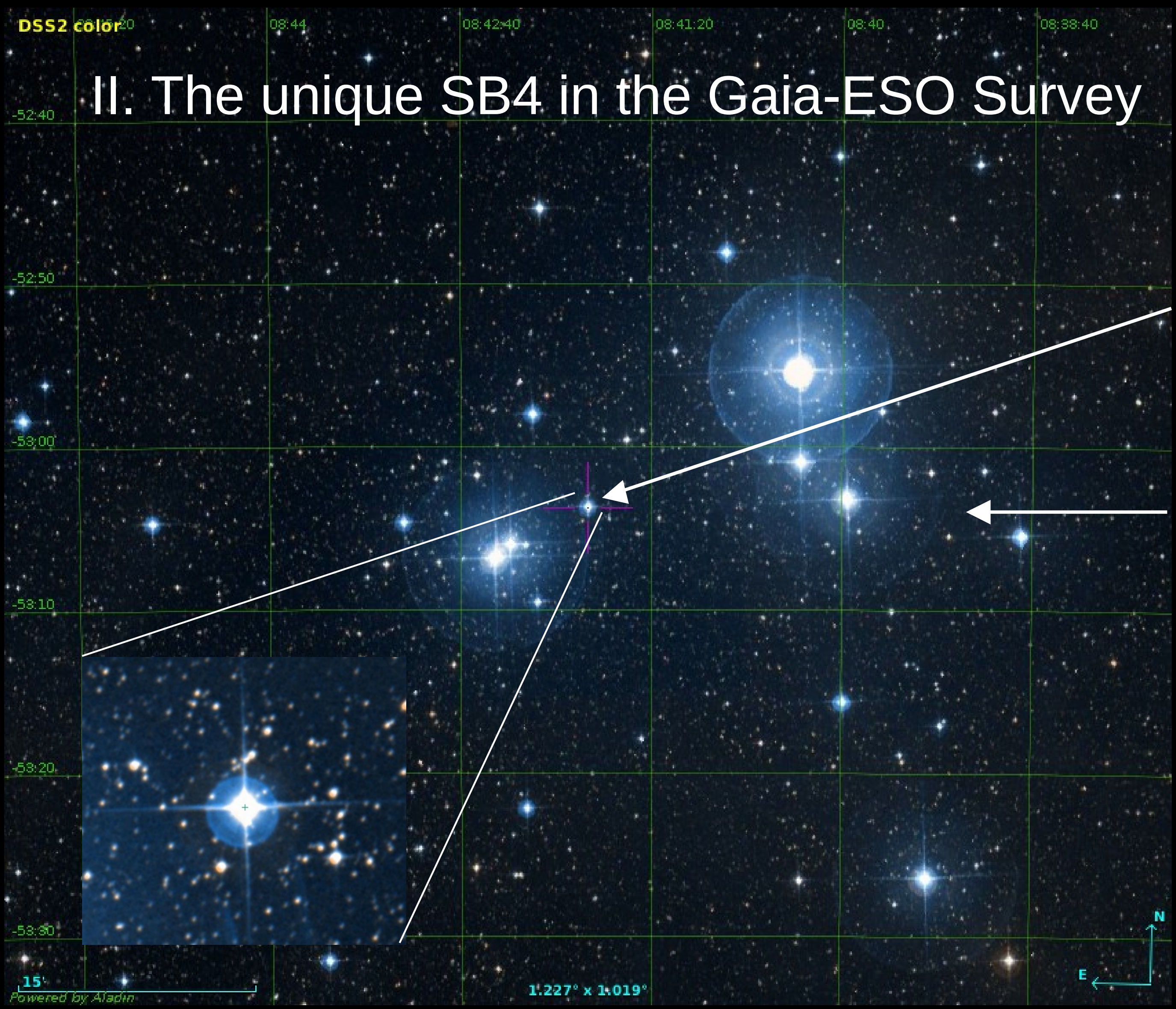


II. The unique SB4 in the Gaia-ESO Survey



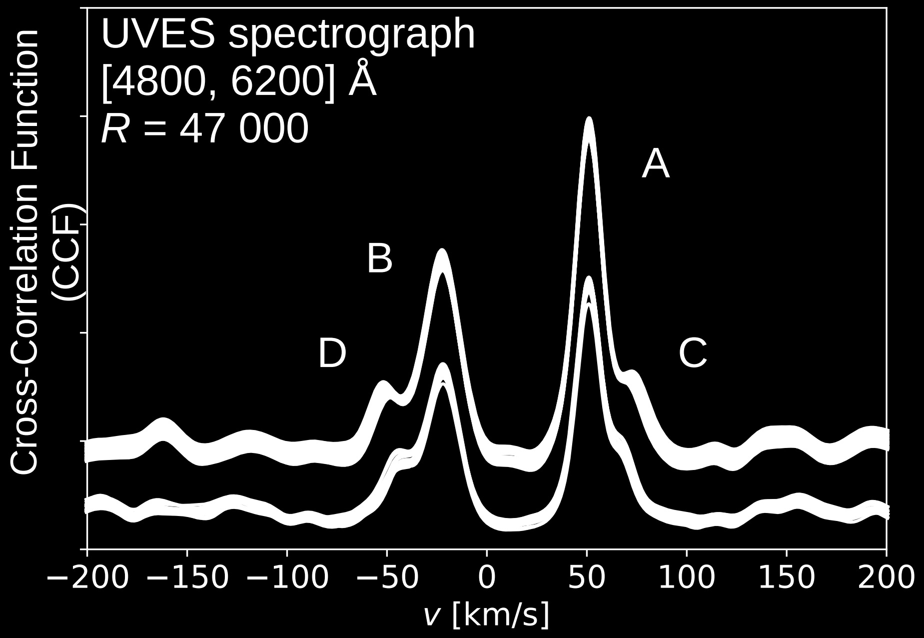
SB4 = spectroscopic quadruple

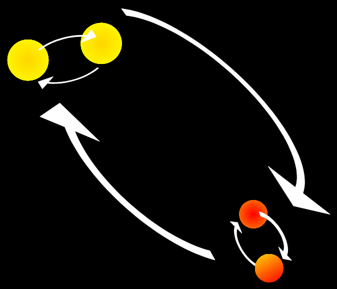
HD 74438 (V = 7.5)
Spectral type: A2V
$M \sim 3\ M_\odot$

Open Cluster IC 2391
N = 325 (Gaia collab. 2018)
v = 14.98 ± 0.17 km/s (Bravi et al. 2018)
d = 146 ± 8 pc (Gaia collab. 2018)
Age = 43^{+15}_{-7} Ma (Randich et al. 2018)

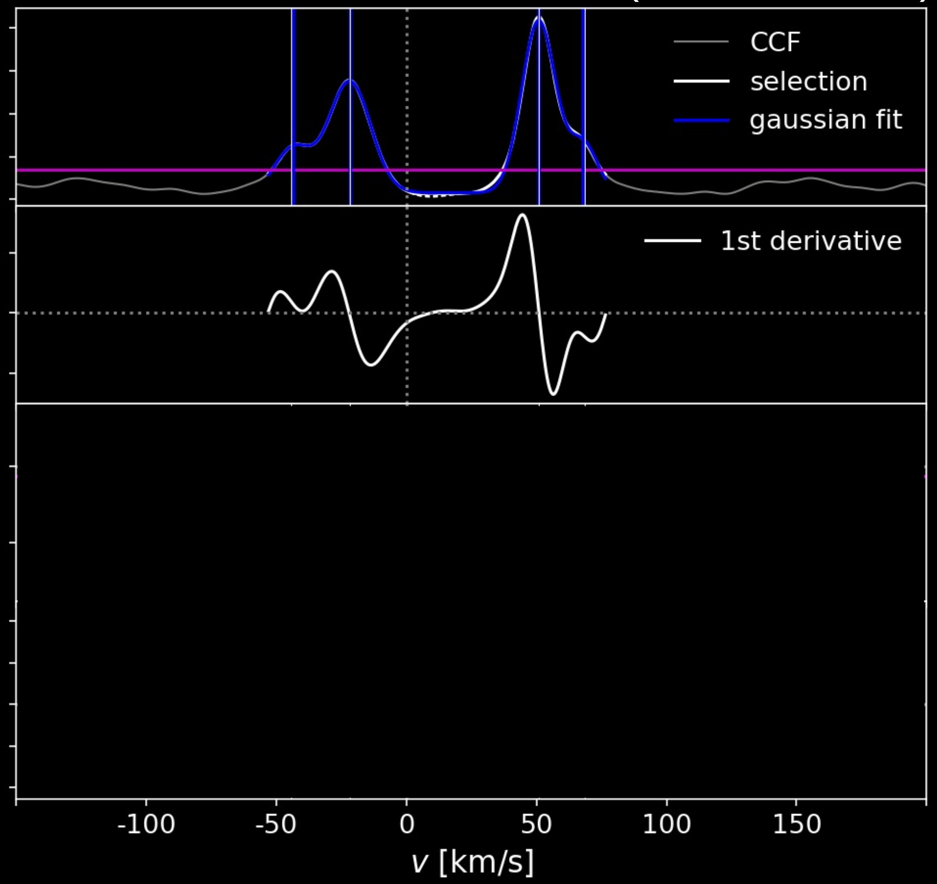
Already suspected to be a triple:
0.9 mag above the main sequence
(Platais et al. 2007)

II. The unique SB4 in the Gaia-ESO Survey

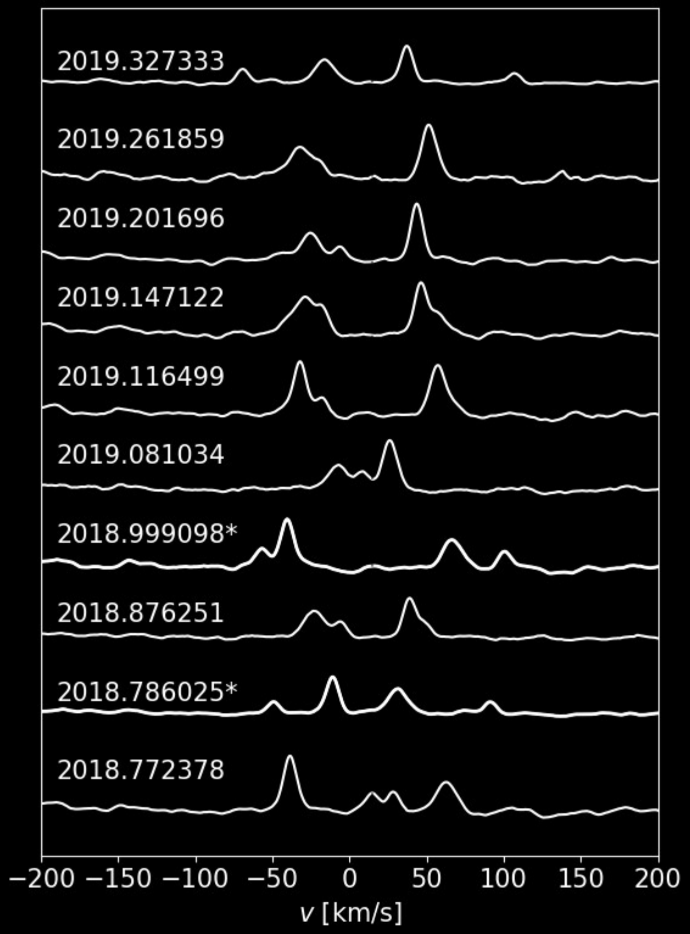




DOE: Detection Of Extrema (Merle et al. 2017)



II. Spectroscopic follow-up with HRS/SALT & HERCULES/UCMJO

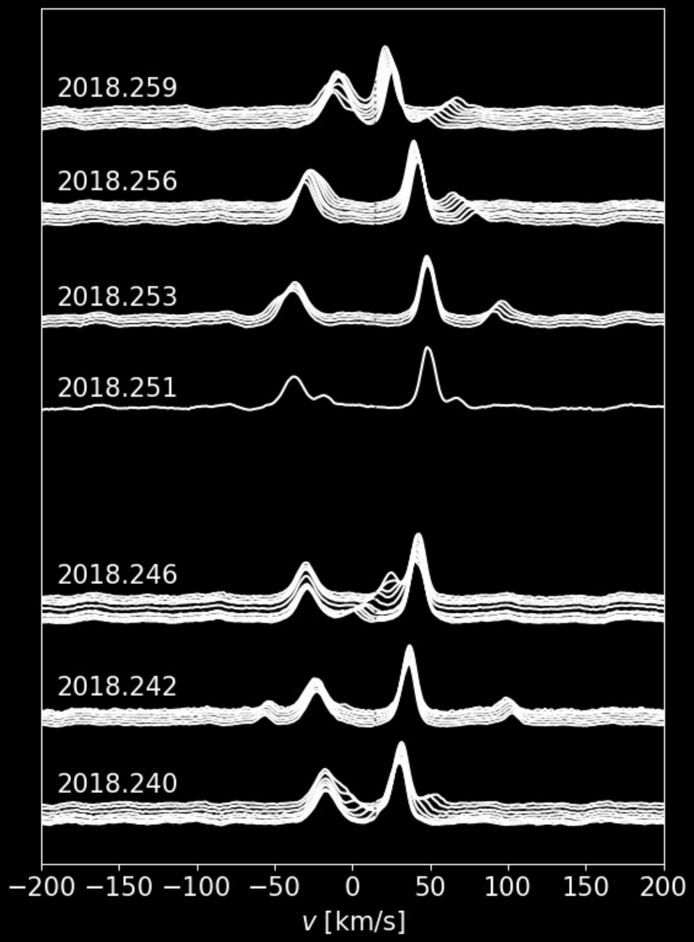


HRS spectrograph
Hearnshaw et al. (2002)

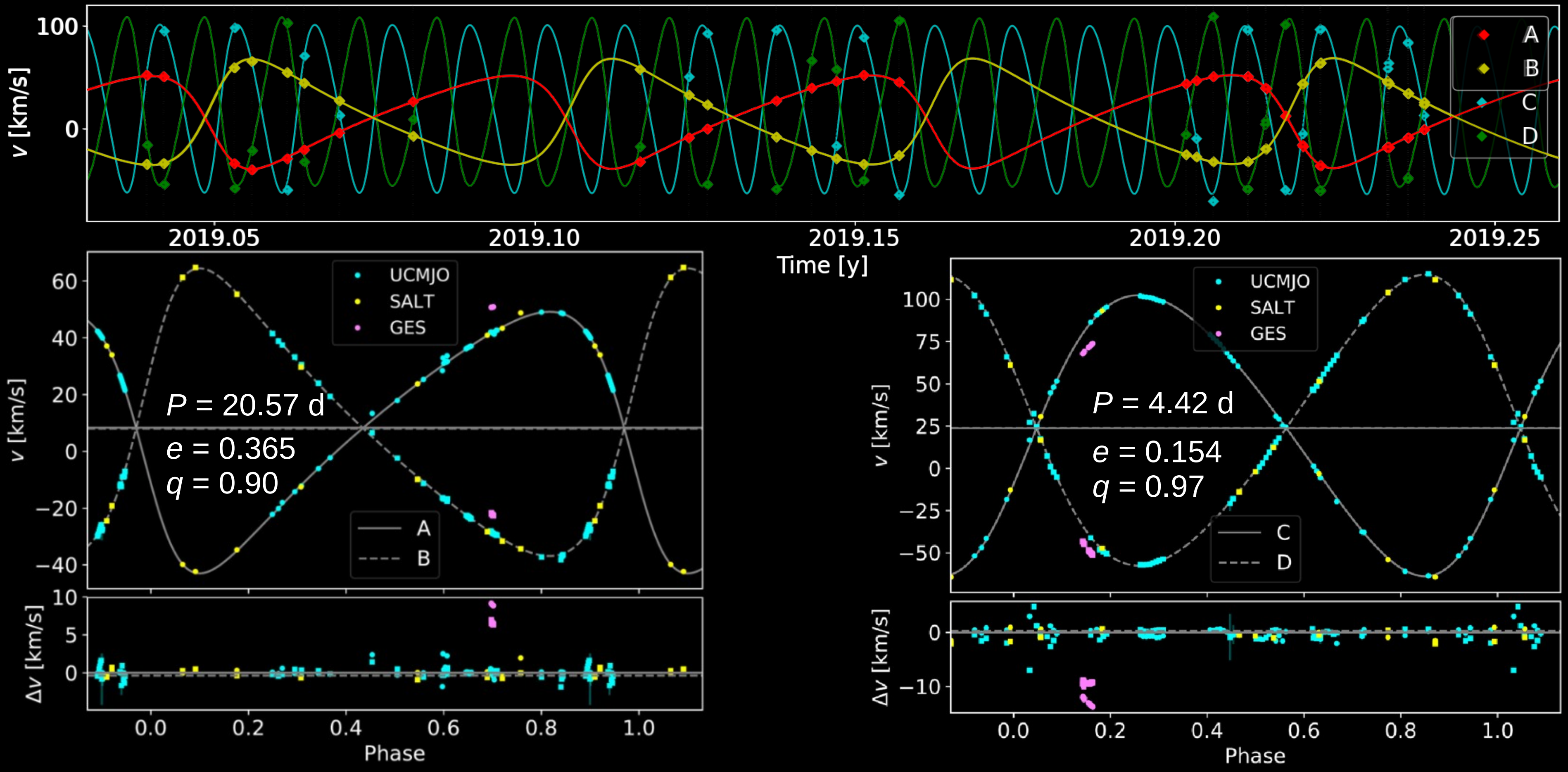
[3830, 8775] Å
R = 65 000

HERCULES spectrograph
Crause et al. (2014)

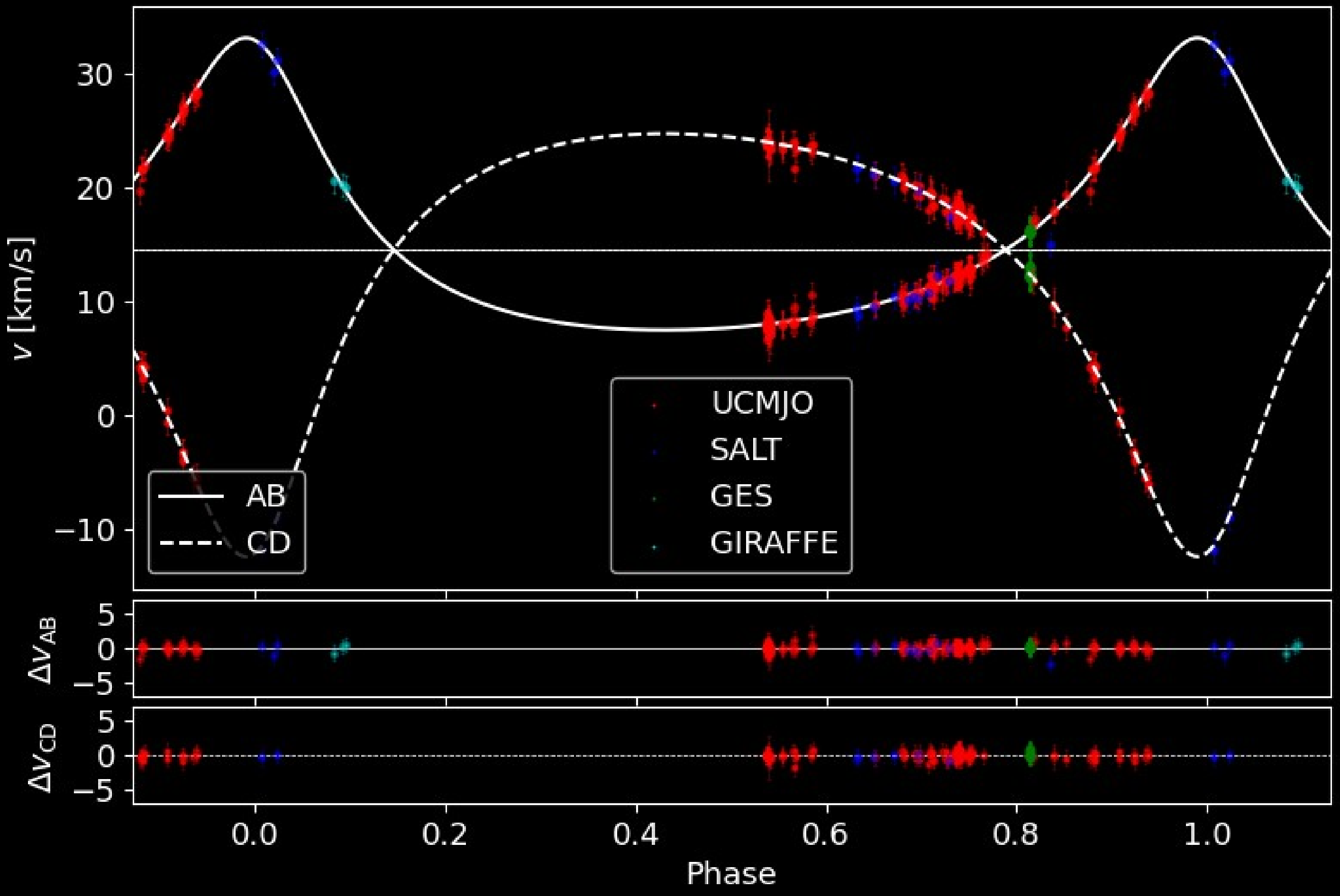
[4160, 7635] Å
R = 41 000



II. Short-period orbital solutions



II. Long-period orbital solution



Period
P = 5.68 ± 0.10 y

Eccentricity
e = 0.458 ± 0.014

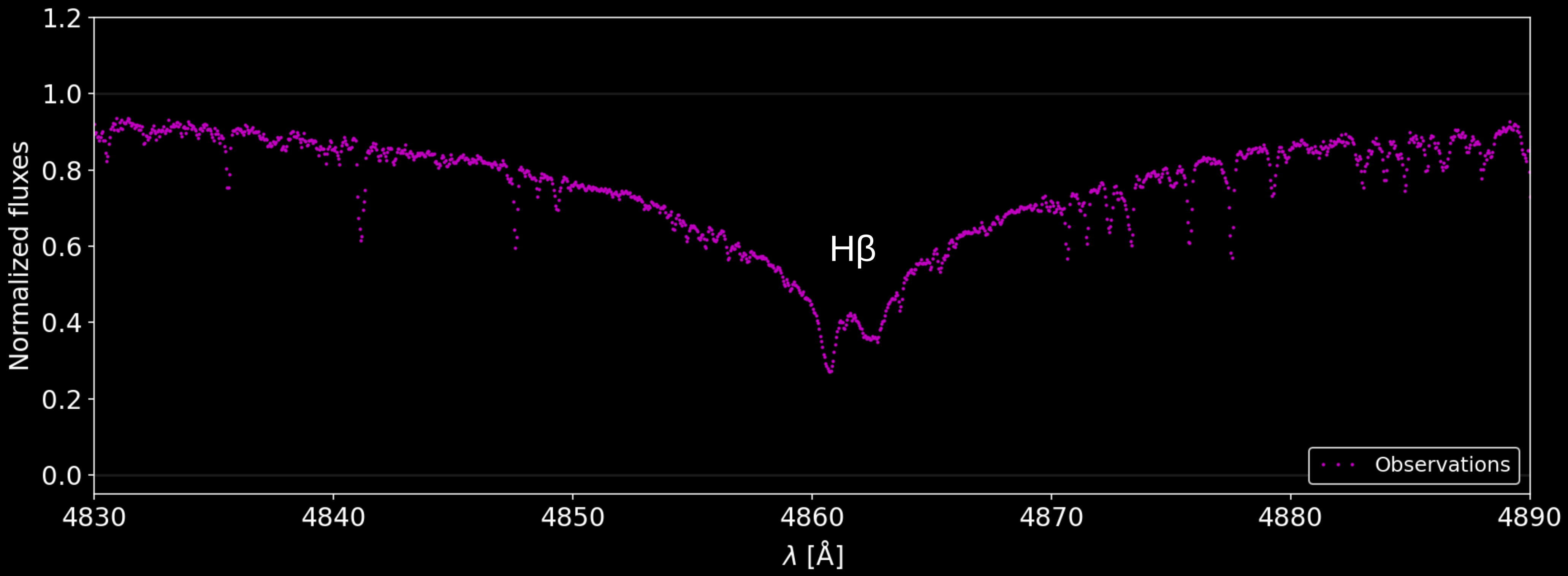
Center of mass velocity
v_0 = 14.54 ± 0.20 km/s

Radial velocity amplitudes
K_{AB} = 12.77 ± 0.28 km/s
K_{CD} = 18.57 ± 0.39 km/s

Periastron time
T_0 = 2 401 089 ± 7 d

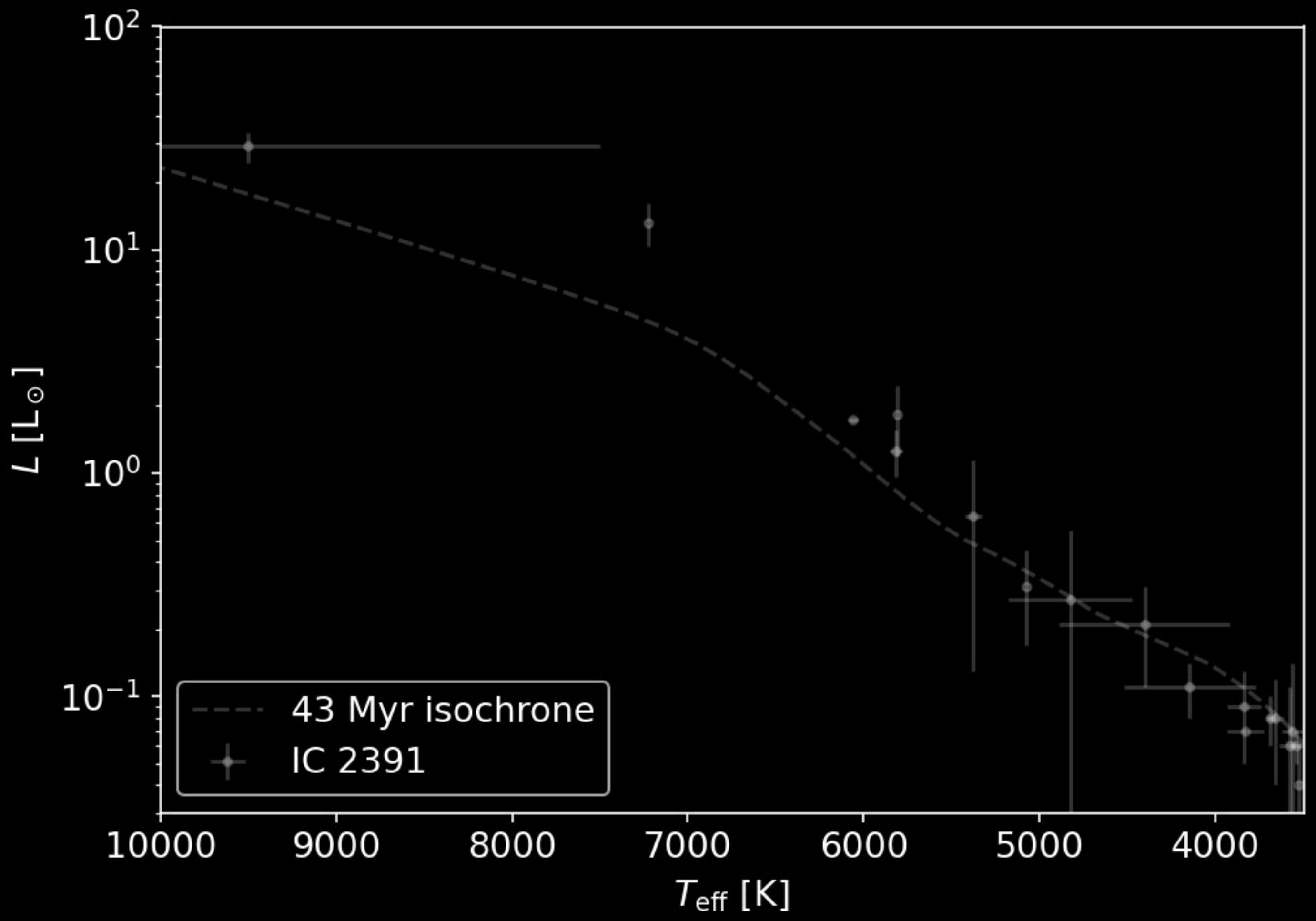
Argument of periastron
ω_{AB} = 10.6 ± 2.2 °

II. Astrophysical parameters



Kurucz's model atmospheres + 1D radiative transfer code Turbospectrum (Plez, 2012)
Spectral fitting in the range [3850 – 5500] Å of HRS/SALT spectra

II. Location in the HR diagram



IC2391 members:
Membership & $T_{\rm eff}$
(Randich et al. 2018)
Gaia DR2 luminosities from Apsis
(Andrae et al. 2018)

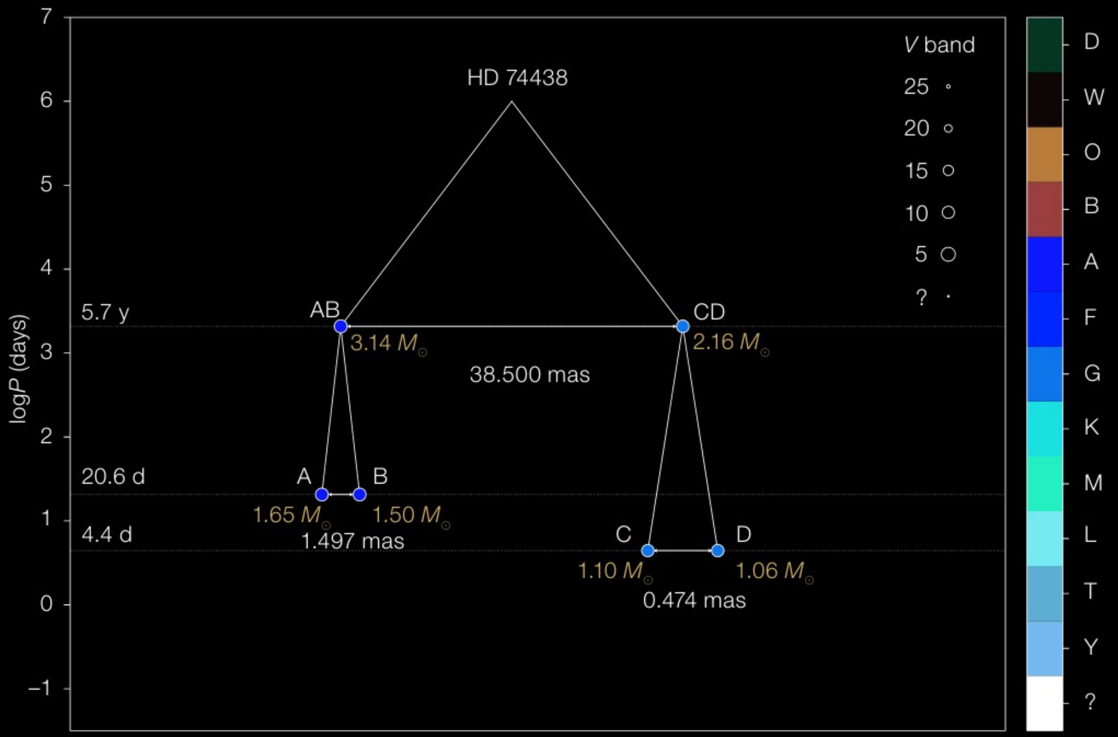
Isochrone at 43 My and
evolutionary tracks
from PARSEC
(Bressan et al. 2012)

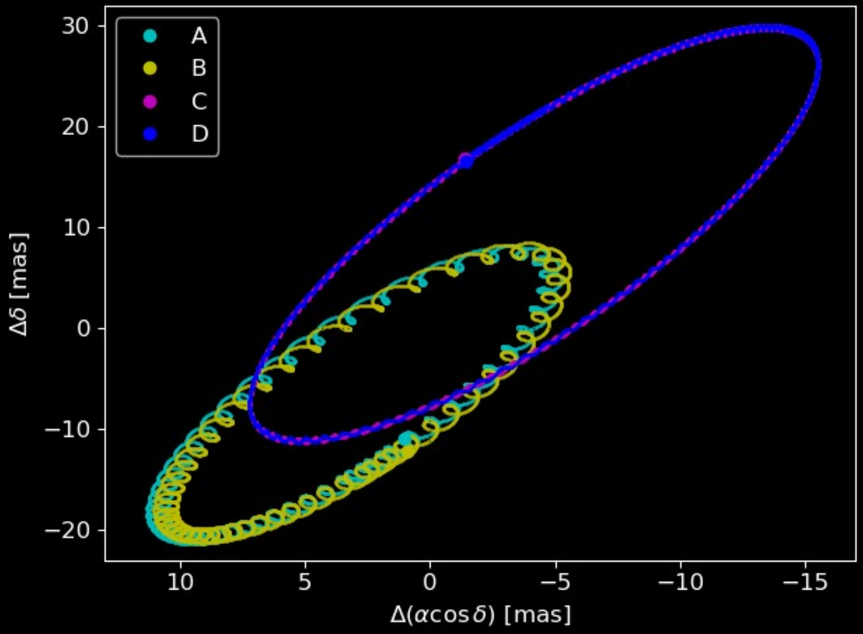
Luminosities are in excellent agreement!

Spectroscopic masses derived

Inclinations and separations deduced

II. Architecture of HD 74438

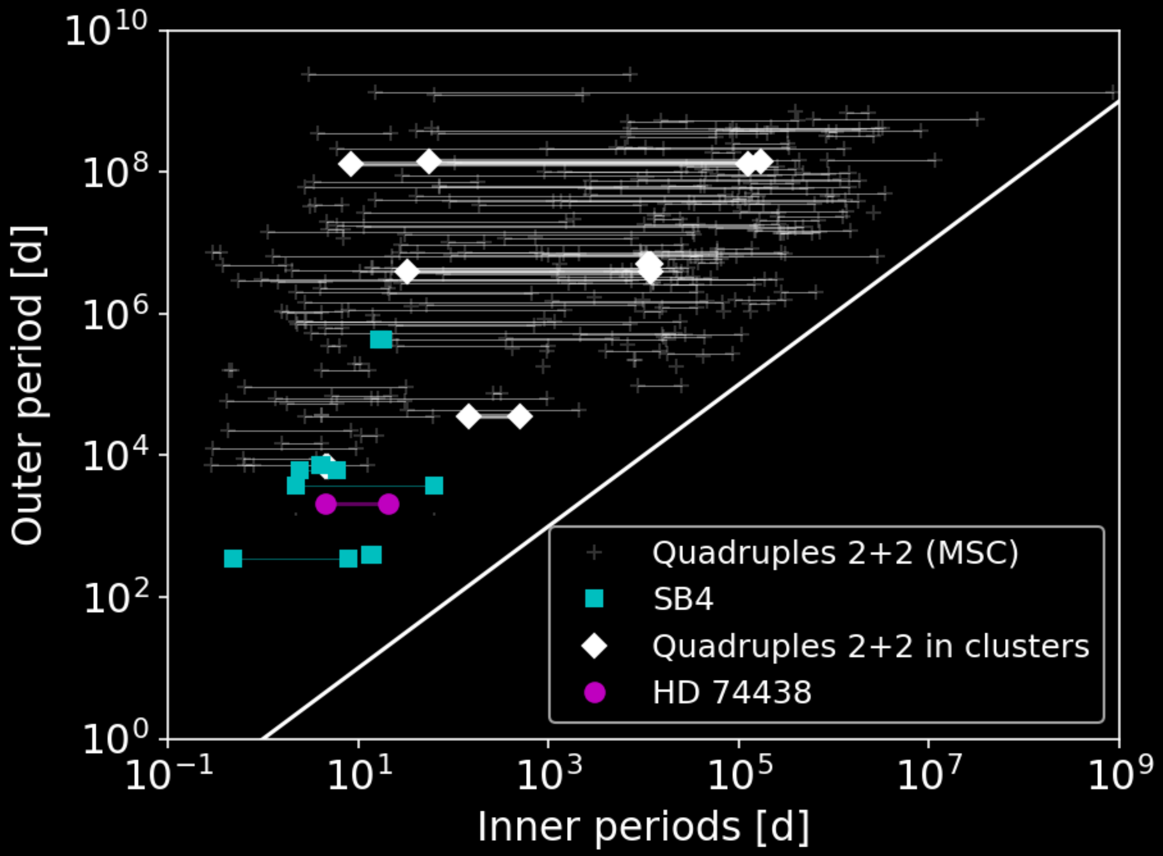




Interferometric observations needed to fully characterize the orientations of the three orbits on the sky

ESO proposal accepted with GRAVITY for period 112!

II. Comparison with other 2+2 quadruples



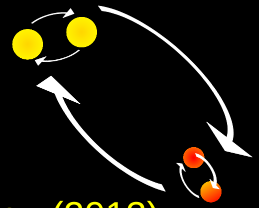
MSC:
Multiple
Stellar
Catalogue
Tokovinin (2018)

Less than 10 SB4 characterized so far:

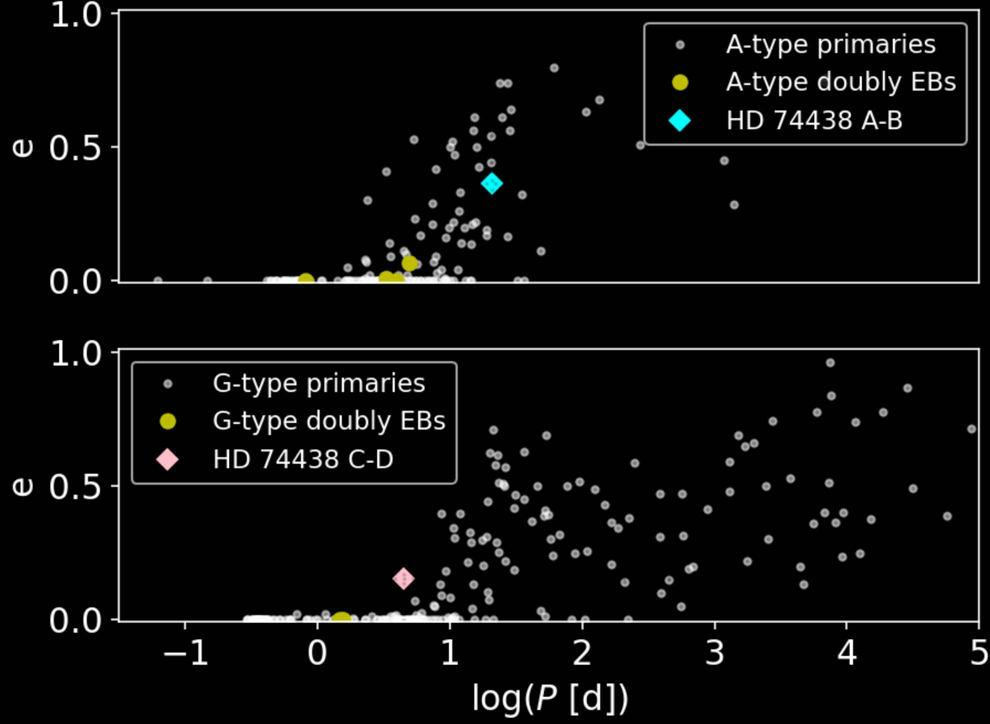
- All dimmer than HD 74438
- 5 of them being doubly EB
- All coplanar or not known

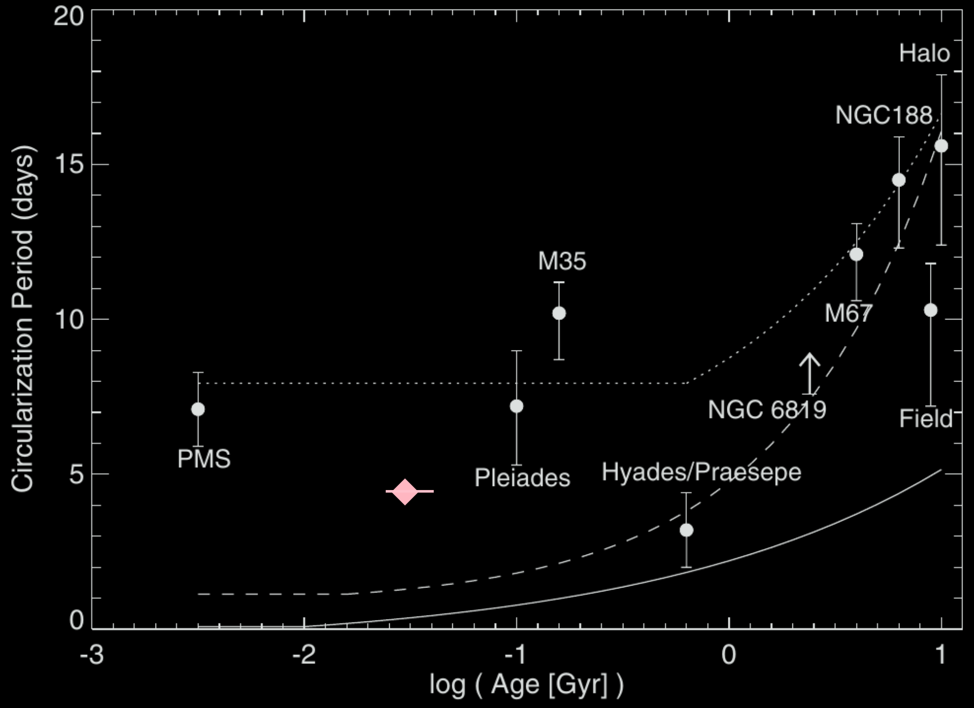
About ~7 quadruples 2+2 in clusters

II. Comparison with SB2 and EB of same spectral types



Geller, Hurley & Mathieu (2013)





The 9th catalogue of spectroscopic orbits (SB9, Pourbaix et al. 2014)
Doubly eclipsing binary (EB) systems (Zasche et al. 2019)
The CD pair is too eccentric for its spectral type

The CD pair has a circularization period smaller than 7-8 d as predicted by Zahn & Bouchet (1989)

II. Multiple star evolution

Secular evolution in triple star: Kozai-Lidov (KL) oscillations (Kozai, 1962, Lidov 1962)

Dynamical interaction in an initially unstable hierarchical triple: Initial mutual inclination *I* in [40, 140]°

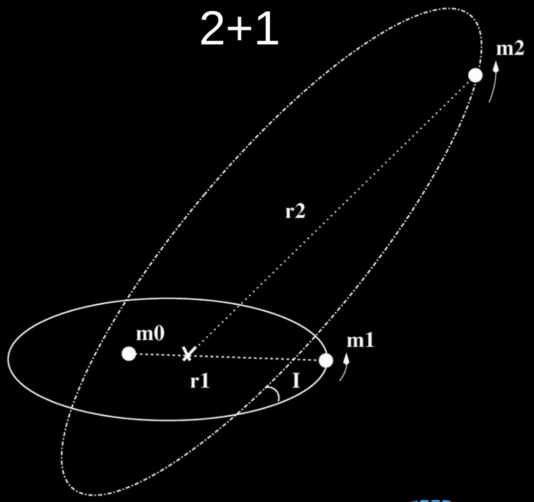
Famous example: Algol system (Baron et. al, 2012)

Pejcha (2013) fist study of KL cycles in quadruples
(see also: Naoz (2016), Hamers (2018), Fang et al. (2018), Tremaine (2020), etc.)

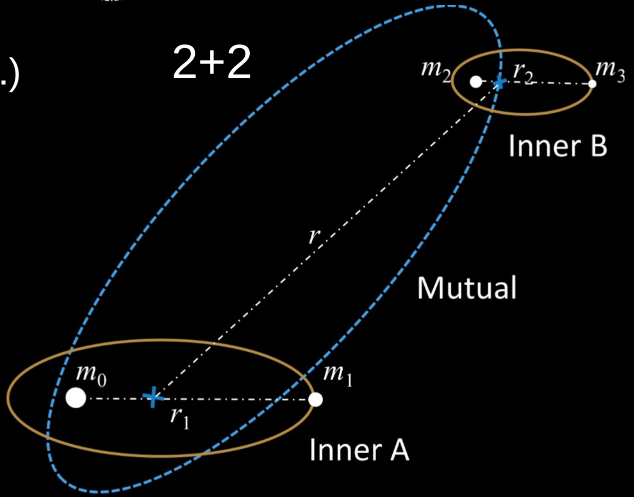
Multiple Stellar Evolution (MSE) code – Hamers et al. (2021)

- Hierarchical architecture: e.g. 1+2, 2+2, 1+3, 2+3, etc.
- Gravitational dynamics
- Stellar evolution
- Binary interaction
- Triple interaction

2+1

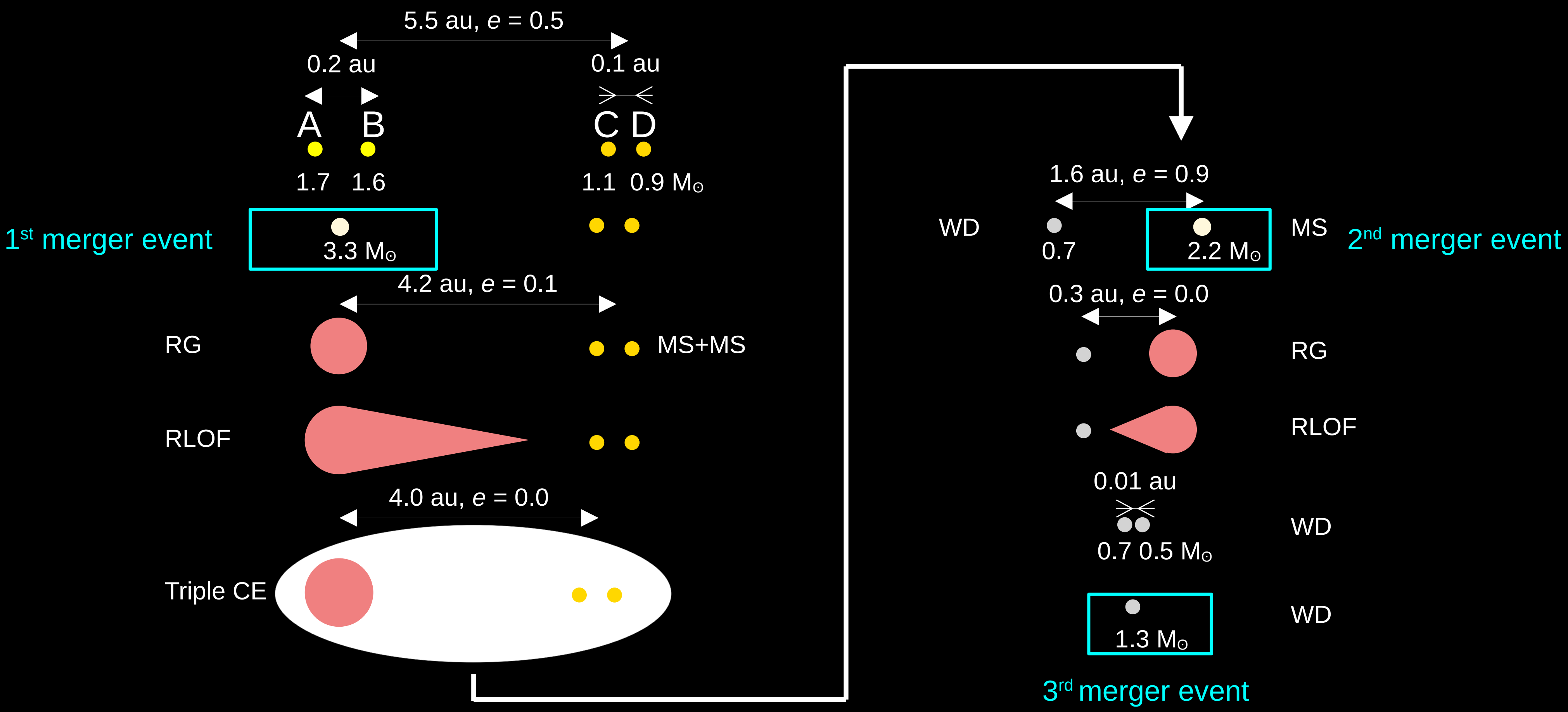


2+2



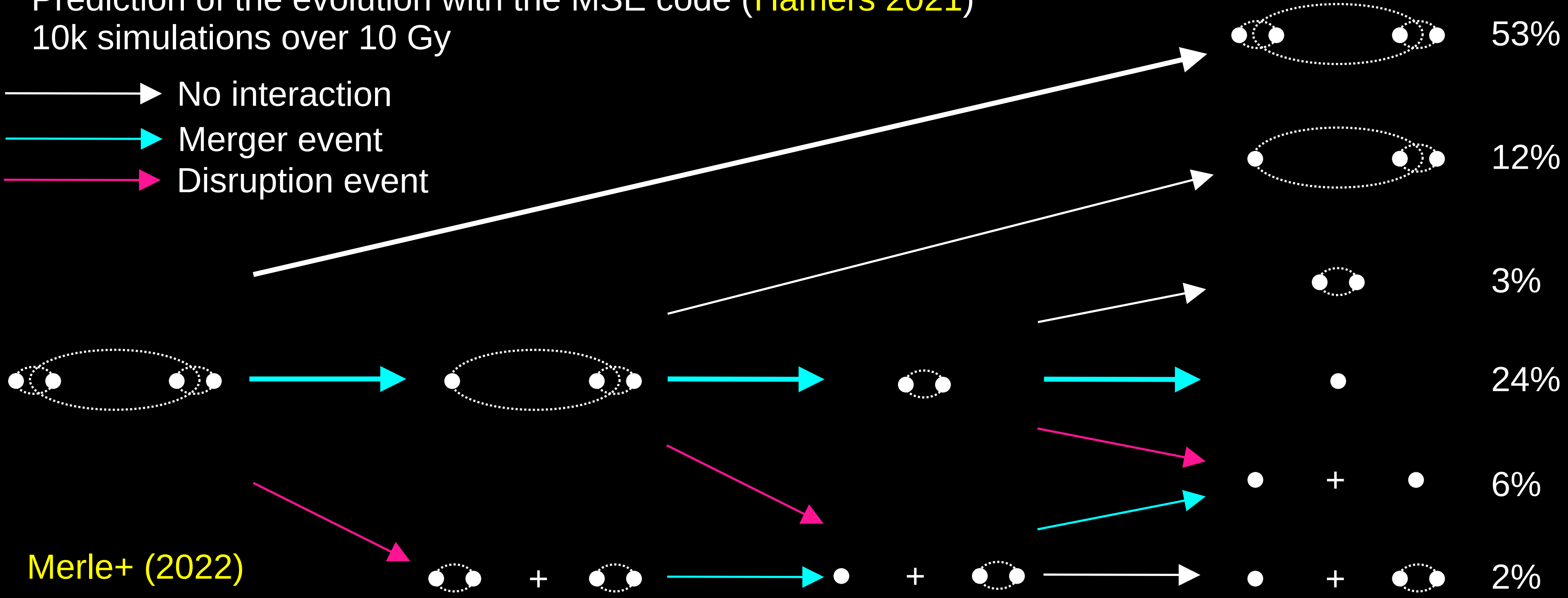
Fang et al. (2018)

II. Example of one realization with MSE (over 2 Gy)



II. The future evolution of HD 74438

Prediction of the evolution with the MSE code (Hamers 2021)
10k simulations over 10 Gy



Merle+ (2022)

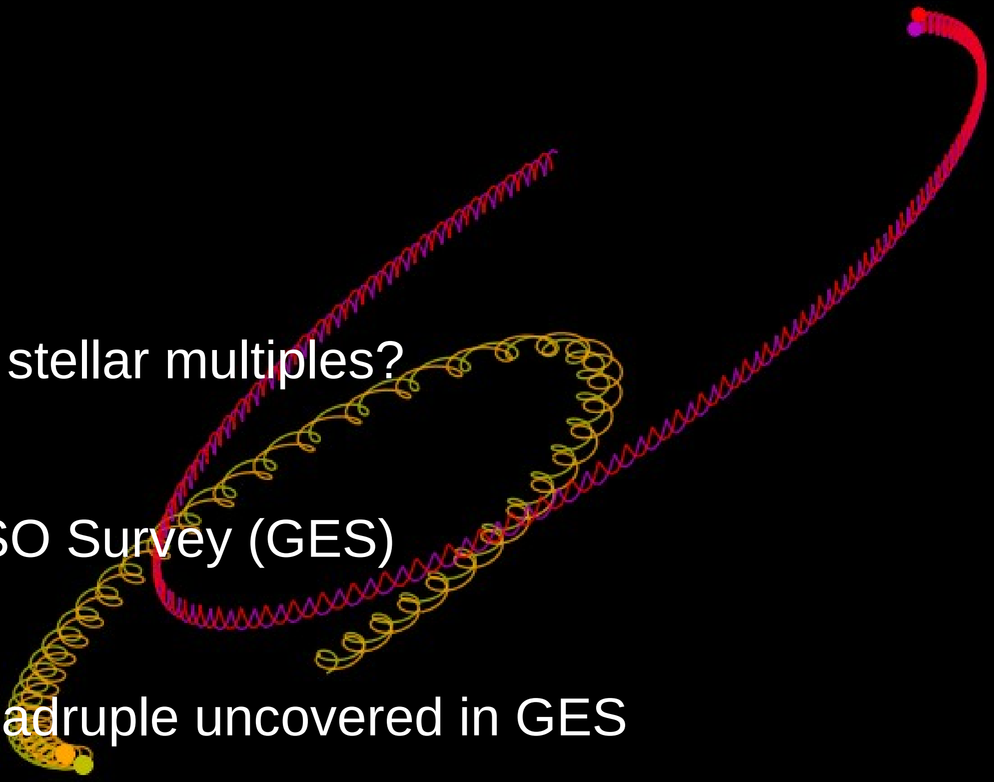
In ~50% of simulated cases, at least 1 merger event
In ~25% of cases, 3 merger events, leading to WD with masses below the Chandrasekhar limit

Introduction: why should we care about stellar multiples?

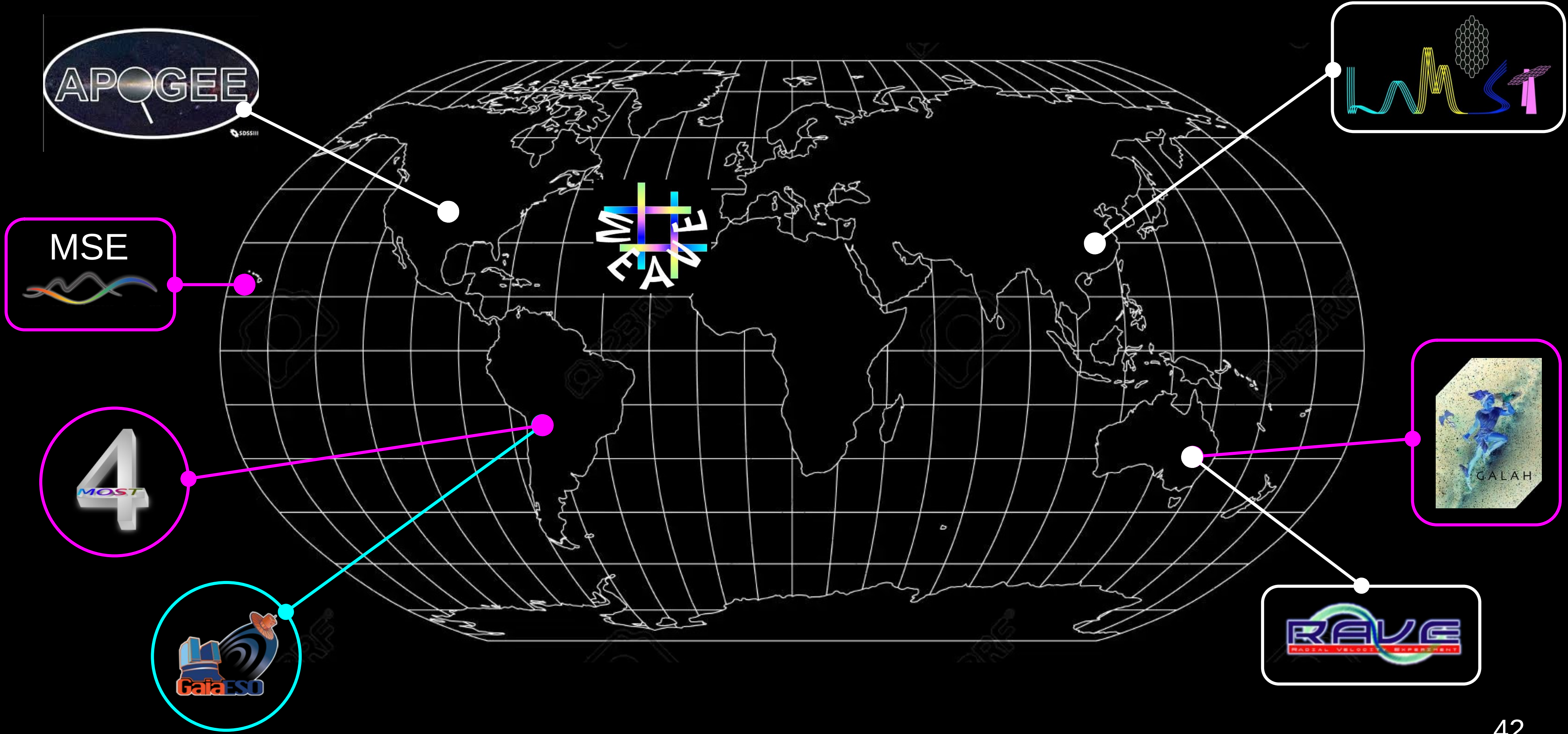
I. Spectroscopic binaries in the Gaia-ESO Survey (GES)

II. HD 74438: a young spectroscopic quadruple uncovered in GES

III. Spectroscopic binaries in other surveys



III. Spectroscopic binaries in other surveys

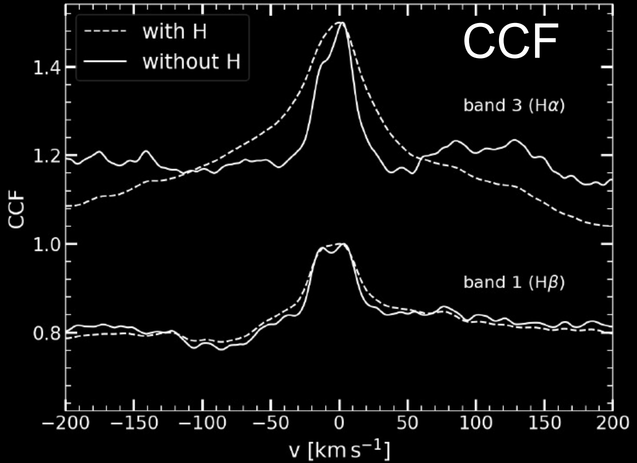


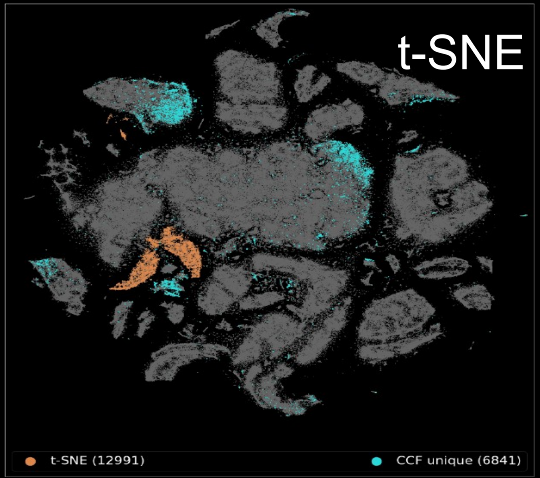
III. SB2 in GALactic Archeology with Hermes (GALAH) survey

~500 000 stars

V magnitude: [12-14]

Resolution: 28 000



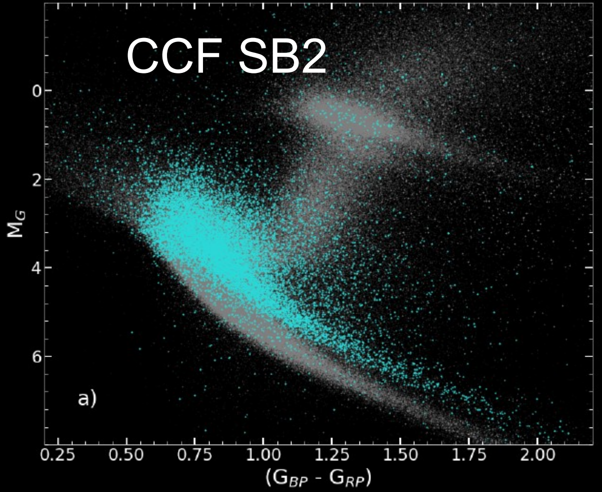


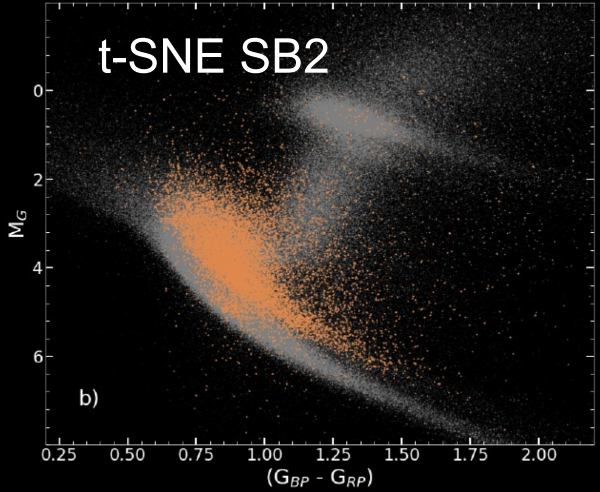
Classical approach (CCF): 14 000
Machine learning approach t-SNE*: 13 000
*t-distributed Stochastic Neighbour Embedding

Combined techniques: 12 000 SB2

Astrophysical characterizationwith Bayesian inference ➔ T_{eff}, log g, [Fe/H] and R

Traven, Feltzing, Merle et al. (2020)
Traven, Cotar, Merle et al. (2019)



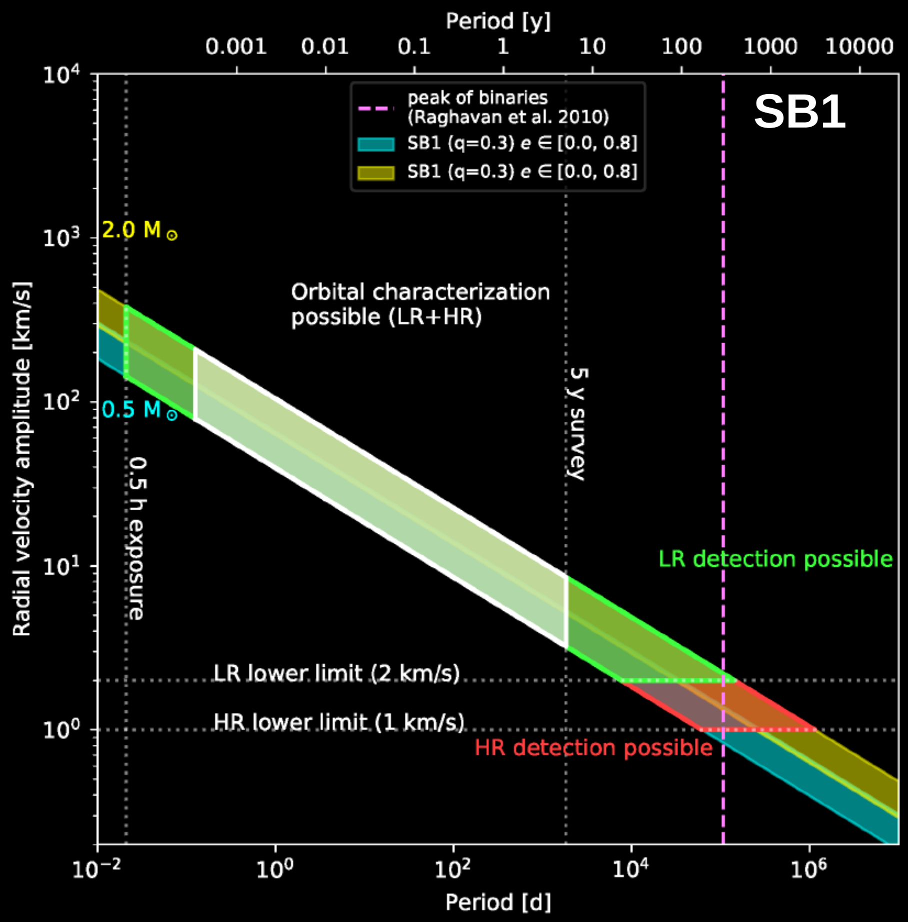


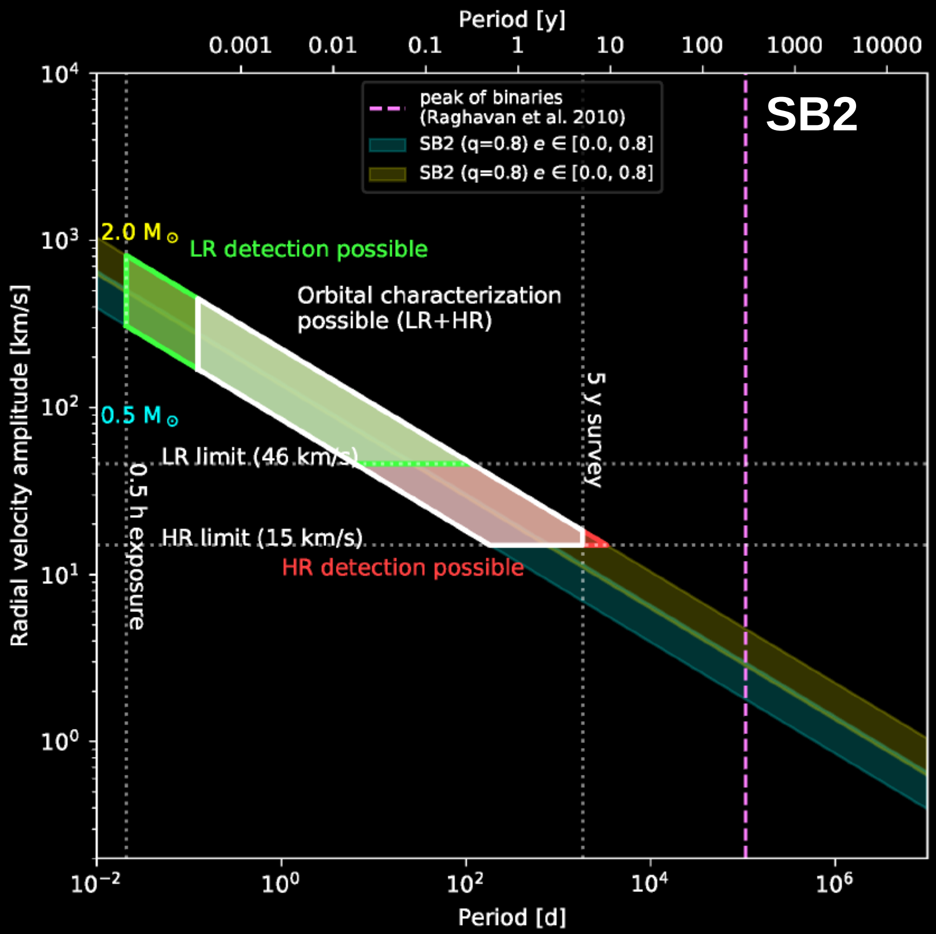
III. Spectroscopic binaries in 4MOST

- 4-m Multi-Object Spectroscopic Telescope on VISTA/ESO
- 2400 fibres per single exposure
- 4 square degrees field of view
- Optical wavelength coverage
- Low-resolution: 4 000 – 8 000, 1 600 fibres, Vmax ~20
- High resolution: ~20 000, 800 fibres, Vmax ~16
- 5 y survey starting in 2024

III. Spectroscopic binaries in 4MOST

$K \propto (M_1/P)^{1/3} \quad \sin i \,/\, \sqrt{(1-e^2)} \quad q/(1+q)^{2/3}$





III. SB in 4MOST: preparation of the observations

Low Resolution Galactic survey (S3) input catalogue: ~ 16 $\times$ 10^6 targets
High Resolution Galactic survey (S4) input catalogue: ~ 8 $\times$ 10^6 targets

Crossmatches of the S3 and S4 input catalogues to setup the cadence of observations:

- OGLE (Soszynski+ 2016)

S3: 1 800 binaries (1 400 EB + 400 ellipsoidal)
S4: 290 binaries (130 EB + 170 ellipsoidal)
Both: median separation 0.1 arcsec, $\Delta V = 0.04 \pm 0.3$

- Survey of Surveys (SoS, Tsantaki+ 2022) (using APOGEE, GALAH, Gaia-ESO, RAVE, & LAMOST, with Gaia as a reference)

S3, S4: 6 900, 26 700 binaries
median separation = 0.02 arcsec

- Gaia DR3 (Gaia collaboration 2022)

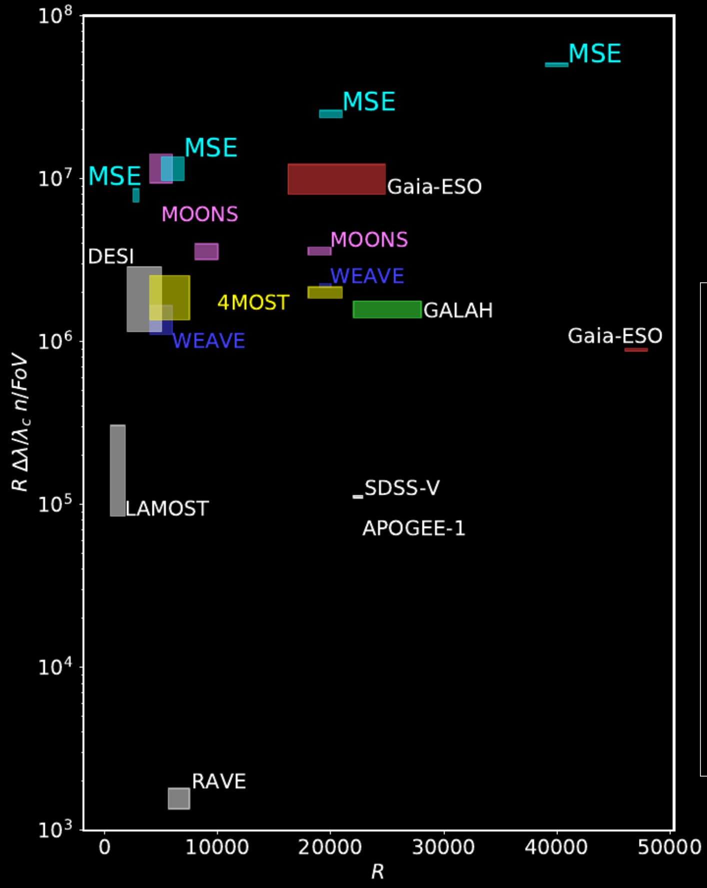
S3: 26 500 binaries (median separation = 0.004 arcsec)
S4: 99 000 binaries (median separation = 0.02 arcsec)

+ preparation of a catalogue of validation on well known SB using DEBCat (Southworth 2015), SB9 (Pourbaix+ 2004), VB+SB catalogue (Piccoti+ 2020), APOGEE DR13+DR16 (Price-Whelan+ 2020, El-Badry et al. 2018), etc.

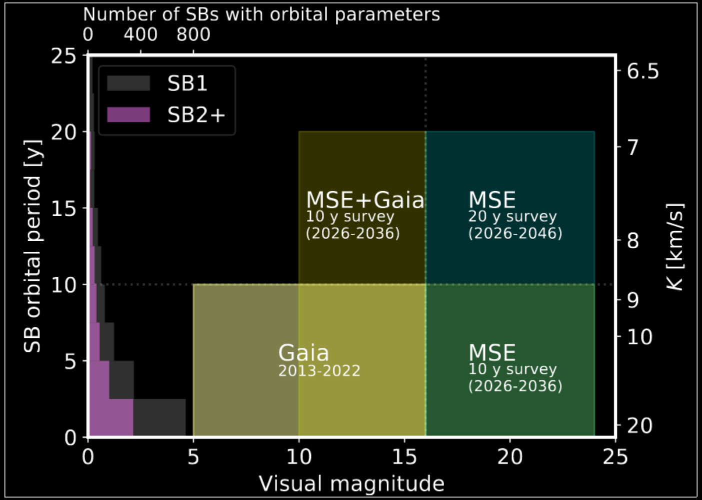
III. SB in the Maunakea Spectroscopic Explorer (MSE)

https://mse.cfht.hawaii.edu/

Rejuvenation of the CFHT
11.25 m aperture telescope
1.5 square degree
Multi-object spectroscopy
(until 4 000)
3 000 < resolving power < 40 000
First light in ~~2026~~ delayed
→ 1 million spectra per month!



Bergemann et al. (2019arXiv190303157B)
Chapter on binaries in The detail science case for MSE, edition 2019



Summary: SB in large surveys

- Detection of SB*n* using 60% of **GES** spectra, with S/N ≥ 3:
  - with ***n* = 1** (Merle et al., 2020),
  - with ***n* = 2, 3 & 4** (Merle et al., 2017)

- **Δ*v* ≥ 2 km/s** for detection of ~ **600 – 800 SB1**
- **Δ*v* ≥ 25 km/s** for detection of **~500 SB2**
- GES **SB1 frequency ~ 10%**, GES **SB2 frequency ~ 2%**

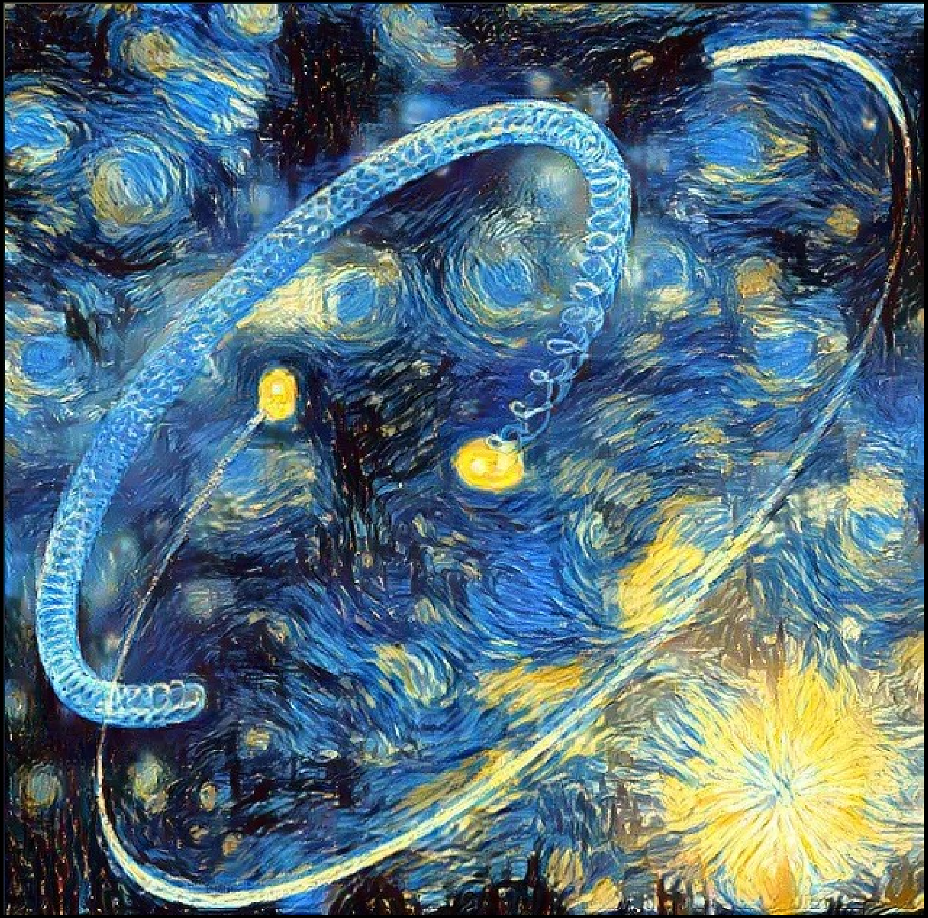
- SB1 frequency increases with decreasing metallicity

- Using improved masks increase the number of SB2 by 1/3 (Van der Swaelmen et al., accepted)

- A unique SB4 (HD 74438) with a 2+2 architecture whose evolution could produce multiple merger events releasing WD mass compatible with sub-Chandrasekhar SN Ia (Merle+ 2022, Nat. Astro., Merle+ 2022, The Messenger)

- Involvement in massive MOS surveys for following and characterizing SB like 4MOST ans MSE

Starry Night style HD 74438



generated with https://creator.nightcafe.studio

BISTRO: Multiple stars detection & characterization

Ground-based spectroscopic surveys medium to high resolution

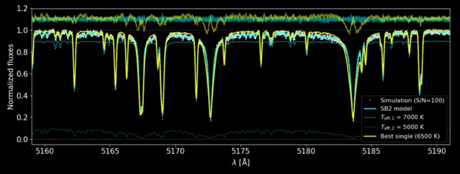
\+

Machine Learning approach

e.g.
The Payne for SB*n* (*n*⩾2)
(collab. Y-S Ting, ANU)

\+

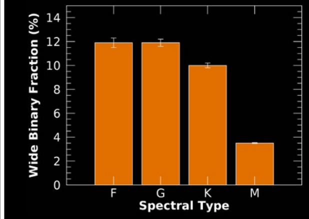
Unresolved SB2
(following El-Badry+ 2018)



\+

Gaia Catalogue of Nearby Stars
⩽ 100 pc
~ 300 000 stars

Astrometry

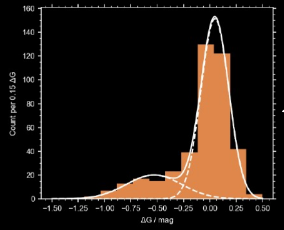


Gaia collaboration 2020

Spectroscopy

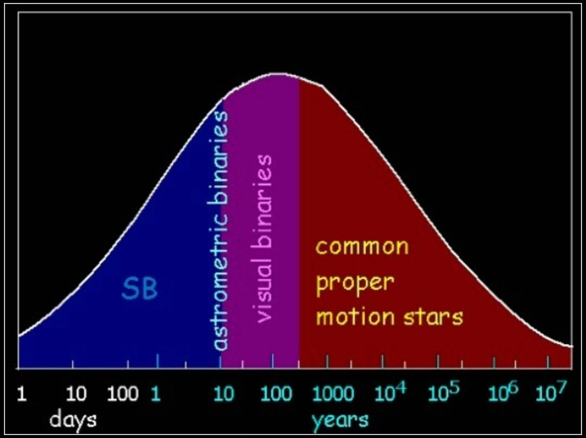
Limitations:
- resolution ~ 11 000
- magnitude ≲ 16

Photometry

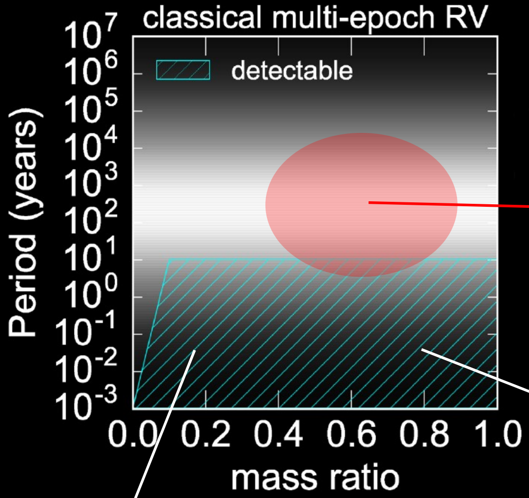


… and future releases

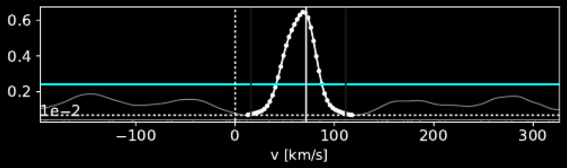
BISTRO: Multiple stars detection & characterization



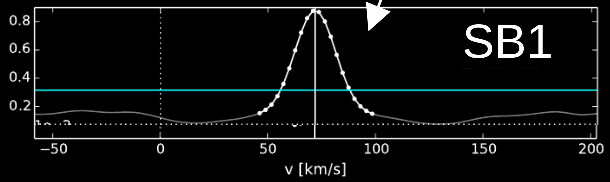
Period distribution



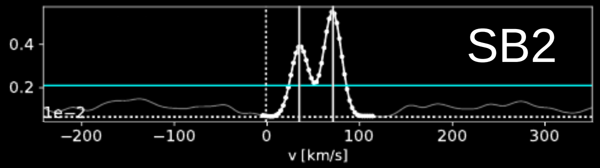
UNRESOLVED SB2



Probe the SB2 properties beyond the 10 y limit

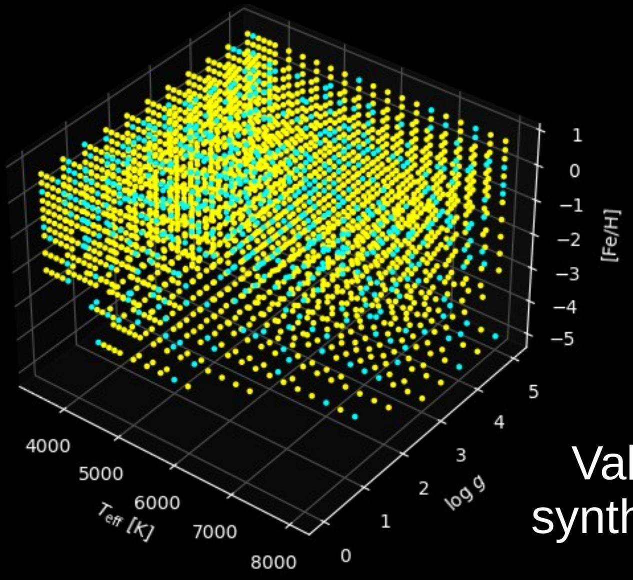


SB1



SB2

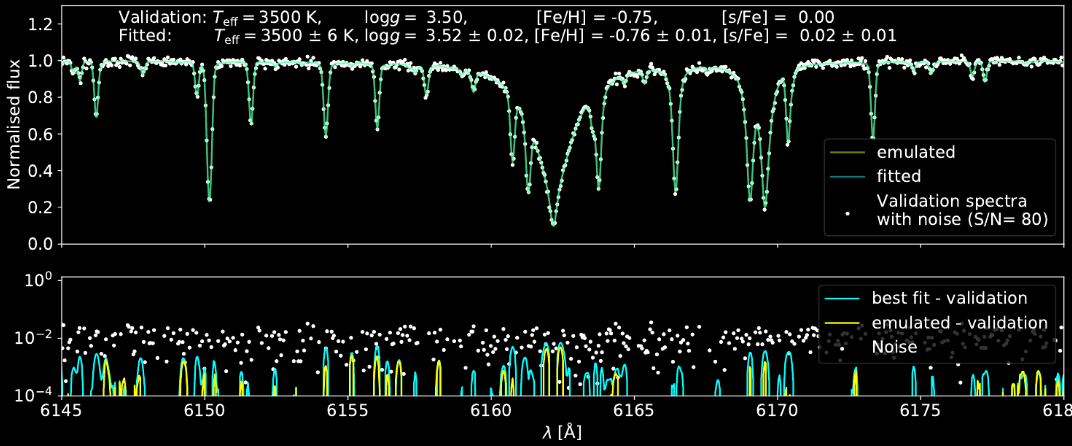
BISTRO: Multiple stars detection & characterization



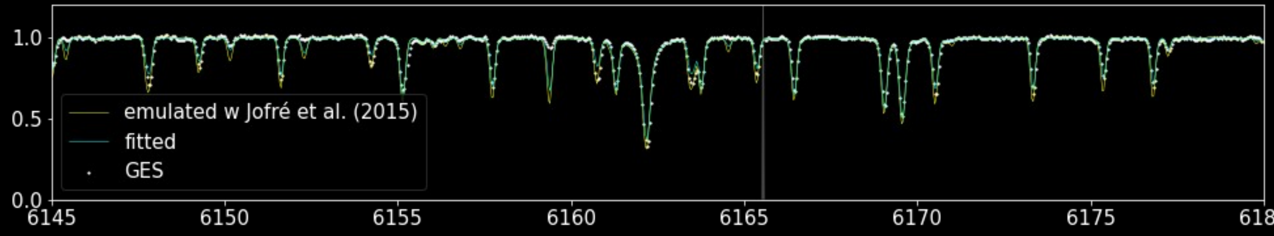
Example for single stars with *The Payne*:

- Training & validation samples from a grid of synthetic spectra
- Input: fluxes ➔ two hidden layers ➔ labels ($T_{\rm eff}$, log$g$, [Fe/H], [s/Fe])

Validation with synthetic spectra



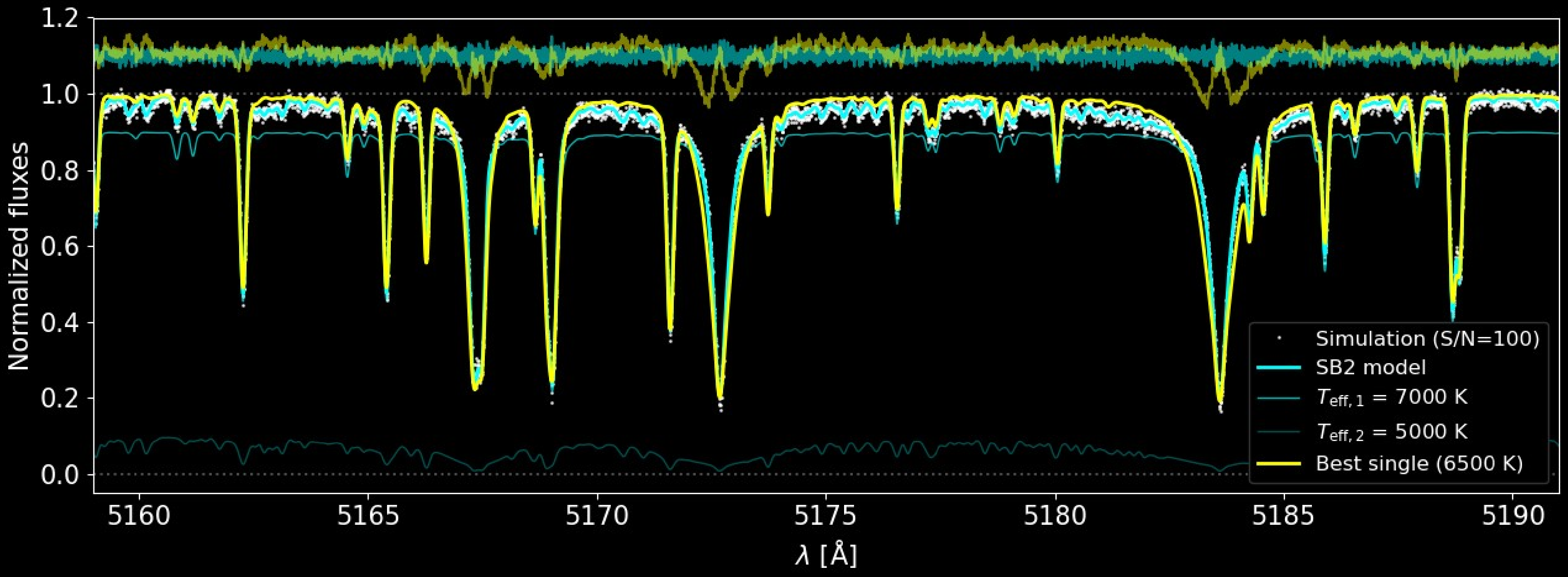
Validation with observed benchmark spectra



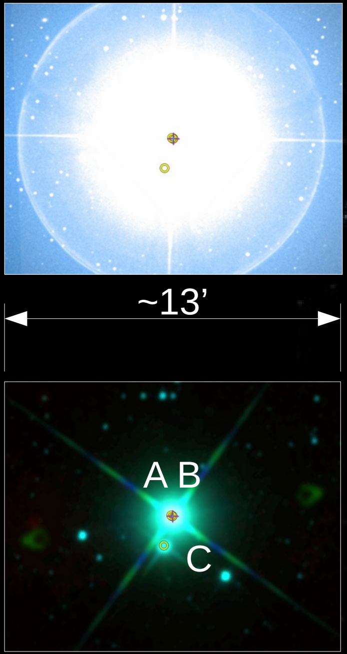
BISTRO: Multiple stars detection & characterization

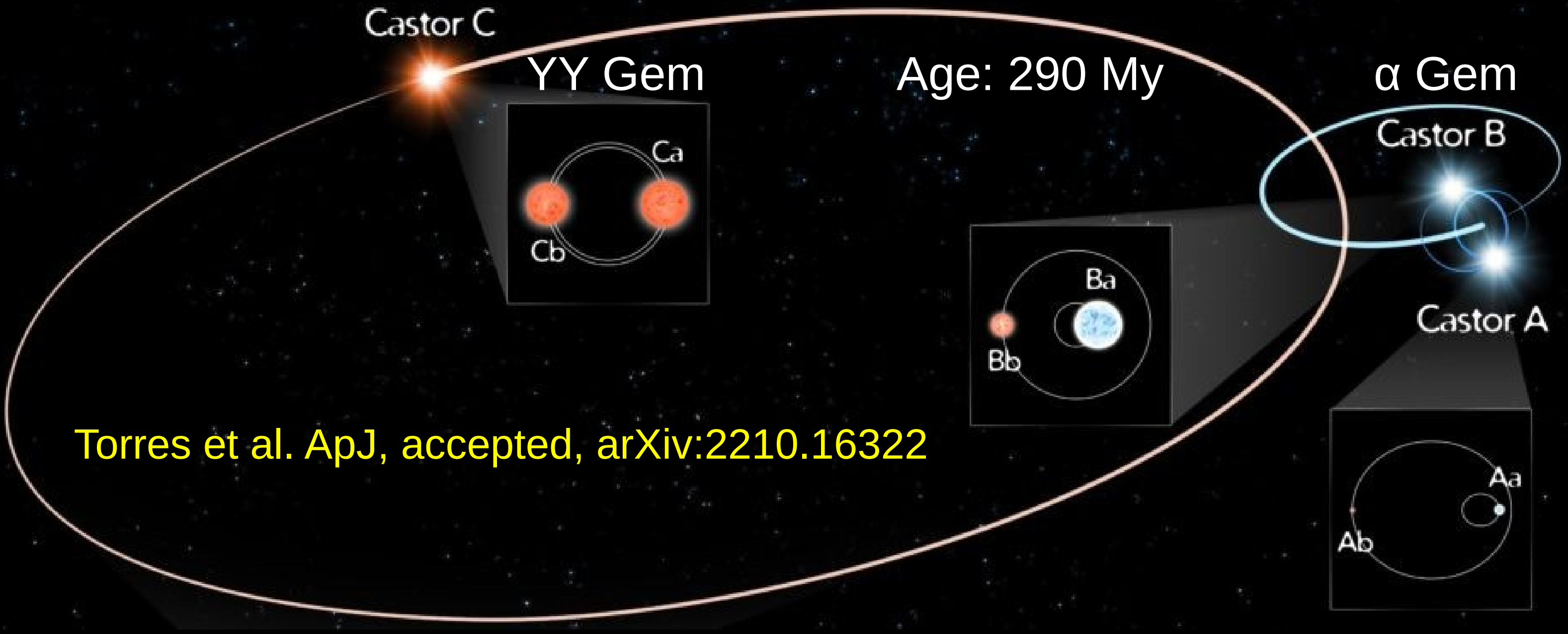
First characterisation: El-Badry+ (2018) on APOGEE spectra in IR (2 500 unresolved SB2)

Also feasible in the visible wavelength range of Gaia-ESO survey and HERMES spectra:



The Castor sextuplet (α Gem (2+2) + YY Gem)





Torres et al. ApJ, accepted, arXiv:2210.16322

Castor Aa, Ab (AIV+MV): 9.2 d, *e* = 0.48, *a* = 0.12 au SB1
Castor Ba, Bb (AIV+MV): 2.9 d, *e* = 0, *a* = 0.05 au SB1
Castor A,B: 459.1 y, e = 0.34, *a* = 102 au (VB)
Castor Ca, Cb (MV+MV): 0.8 d, e = 0, *a* = 0.02 au EB+SB2
Castor AB,C: ~14.5 ky, a > 1060 au

Other SB4

Merle+ 2022, Nat. Astron.

1. BD−22°5866: K and M binaries with V = 10.4. The K binary is also an EB with a 2.2 d period. No spectral decomposition [6]; unknown inclinations.
2. V994 Her: SB4 composed of 2 pairs of eclipsing binaries: (B8V+A0V) and (A2V+A4V) with 2.1 and 1.4 d periods [7]. The outer period is 2.9 y [8].
3. KIC 4247791: SB4 system with two eclipsing binaries made of 4 F-type stars (F0, F2, F7, F8) with 4 d periods for each EB and V = 11.6. No spectral decomposition [9];
4. KIC 7177553: SB4 system consisting of two eccentric binaries with similar periods of about 17 d where one of the two binaries is eclipsing, V = 11.3. The four components are G-type stars of similar masses [10].
5. EPIC 220204960: SB4 system with two interacting eclipsing binaries made of 4 M stars with periods of 13-14 d with an outer period of about 1 y, and V = 12.7 [11].
6. V482 Per: SB4 system (B9, A1, A7, A7) with 2 EB with 2.4 and 6 d with an outer period of 16.6 y, and V = 10.3 [12].
7. VW LMi: SB4 system (F-G spectral types) which is the tightest quadruple system with 2+2 hierarchy yet discovered, with 0.48, 7.93 and 355 d periods and V = 8.0 [13].
8. CzeV1731: SB4 system with 2 twin eclipsing binaries and an outer period estimated at 34 y [14].
9. TIC 454140642: a coplanar SB4 system with 2 eclipsing binaries with V = 10.4. The outer period is estimated at 432 d [15].

[6] Shkolnik, E. *et al.*, BD -22 5866: A Low-Mass, Quadruple-lined Spectroscopic and Eclipsing Binary, *Astrophys. J.*, **682**, 1248-1255

[7] Lee, C.-U., *et al.*, V994 Herculis: the multiple system with a quadruple-lined spectrum and a double eclipsing feature, *Mon. Not. R. Astron. Soc.*, **389**, 1630-1636 (2008)

[8] Zasche, P. & Uhlař, R., Updated study of the quintuple system V994 Herculis, *Astron. Astrophys.*, **588**, A121 (2016)

[9] Lehmann, H. *et al.*, KIC 4247791: a SB4 system with two eclipsing binaries (2EBs). A quadruple system?, *Astron. Astrophys.*, **541**, A105 (2012)

[10] Lehmann, H. et al., KIC 7177553: A Quadruple System of Two Close Binaries, *Astrophys. J.*, **819**, 33 (2016)

[11] Rappaport, S. *et al.*, EPIC 220204960: A Quadruple Star System Containing Two Strongly Interacting Eclipsing Binaries, *Mon. Not. R. Astron. Soc.*, **467**, 2160-2179 (2017)

[12] Torres, G. *et al.*, The Quadruple-lined, Doubly Eclipsing System V482 Persei, *Astrophys. J.*, **846**, 115 (2017)

[13] Pribulla, T., *et al.*, VW LMi: tightest quadruple system known. Light-time effect and possible secular changes of orbits, *Mon. Not. R. Astron. Soc.*, **390**, 798-806 (2008)

[14] Zasche, P. et al., CzeV1731: The unique doubly eclipsing quadruple system, *Astron. Astrophys.*, **642**, 63 (2020)

[15] Kostov, V. B. et al., TIC 454140642: A Compact, Coplanar, Quadruple-lined Quadruple Star System Consisting of Two Eclipsing Binaries, *Astrophys. J.*, **917**, 93 (2021)

Astrophysical parameters of HD 74438

	Component	A	B	C	D	Unresolved
	Spectral Type	A5	A9	G5	G9	–
	T_{eff} [K]	8250 ± 250	7500 ± 250	5625 ± 410	5375 ± 410	-
	L [$L_\odot$]	8.87 ± 1.40	5.72 ± 0.95	0.64 ± 0.51	0.48 ± 0.32	15.71 ± 1.80
	R [$R_\odot$]	1.46 ± 0.15	1.42 ± 0.15	0.84 ± 0.36	0.80 ± 0.29	-
spectroscopic	M [$M_\odot$] [a]	1.70 ± 0.06	1.54 ± 0.06	0.96 ± 0.14	0.87 ± 0.14	5.07 ± 0.22
dynamical	M [$M_\odot$] [b]	1.64 ± 0.06	1.48 ± 0.06	1.09 ± 0.04	1.06 ± 0.04	5.27 ± 0.10

Orbital parameters of HD 74438

	A-B	C-D	AB-CD
P [d]	20.5729 ± 0.0003	4.4243 ± 0.0001	2074.2 ± 3.5
e	0.3692 ± 0.0001	0.1535 ± 0.0003	0.458 ± 0.015
ω_1 [rad] [(a)]	1.8780 ± 0.0003	-1.946 ± 0.002	0.185 ± 0.039
T_0 - 2400000 [d]	58 605.9 ± 0.1	58 684.5 ± 0.1	59165.8 ± 5.1
v_0 [km s^{-1}]	-	-	14.5 ± 0.2
K_1 [km s^{-1}] [(b)]	45.81 ± 0.09	83.2 ± 0.1	12.8 ± 0.3
K_2 [km s^{-1}] [(b)]	50.77 ± 0.09	85.5 ± 0.1	18.5 ± 0.4
q_{dyn}	0.902 ± 0.002	0.973 ± 0.002	0.692 ± 0.003
q_{spec}	0.91 ± 0.05	0.91 ± 0.22	0.58 ± 0.11
i [°]	(52.5 or 127.5) ± 1.5	(84.0 or 96.0) ± 0.9	(73.2 or 106.8) ± 2.7 [(c)]
a [au]	0.215 ± 0.002	0.0681 ± 0.001	5.54 ± 0.04
Ω [°]	-	-	333° or 274°
μ''_{phot} [mas/y]	-	-	13.0

Summary of all simulations

Description	Fraction	Final outcomes	Fraction
No interaction	0.535 ± 0.007	Quadruple	0.535 ± 0.007
Mergers all	0.465 ± 0.007	Single	0.236 ± 0.005
CE	0.298 ± 0.005	Triple	0.117 ± 0.003
Collision	0.461 ± 0.007	Two Single	0.058 ± 0.002
Dynamical instability	0.010 ± 0.001	Binary	0.030 ± 0.002
Triple RLOF	0.363 ± 0.006	Binary+Single	0.024 ± 0.002
Triple CE	0.360 ± 0.006		
Number of final remnants	**Fraction**	**Triple CE outcomes**	**Fraction**
1	0.236 ± 0.005	Triple	0.036 ± 0.003
2	0.088 ± 0.003	Merger(s)	0.705 ± 0.014
3	0.141 ± 0.004	Binary+Single	0.152 ± 0.006
4	0.535 ± 0.007	Indeterminate	0.107 ± 0.005

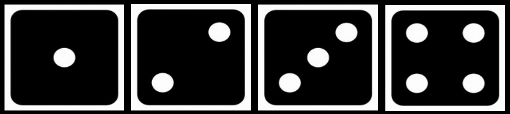
3 mergers

2 mergers

1 merger

Multiplicity statistics in late-type stars

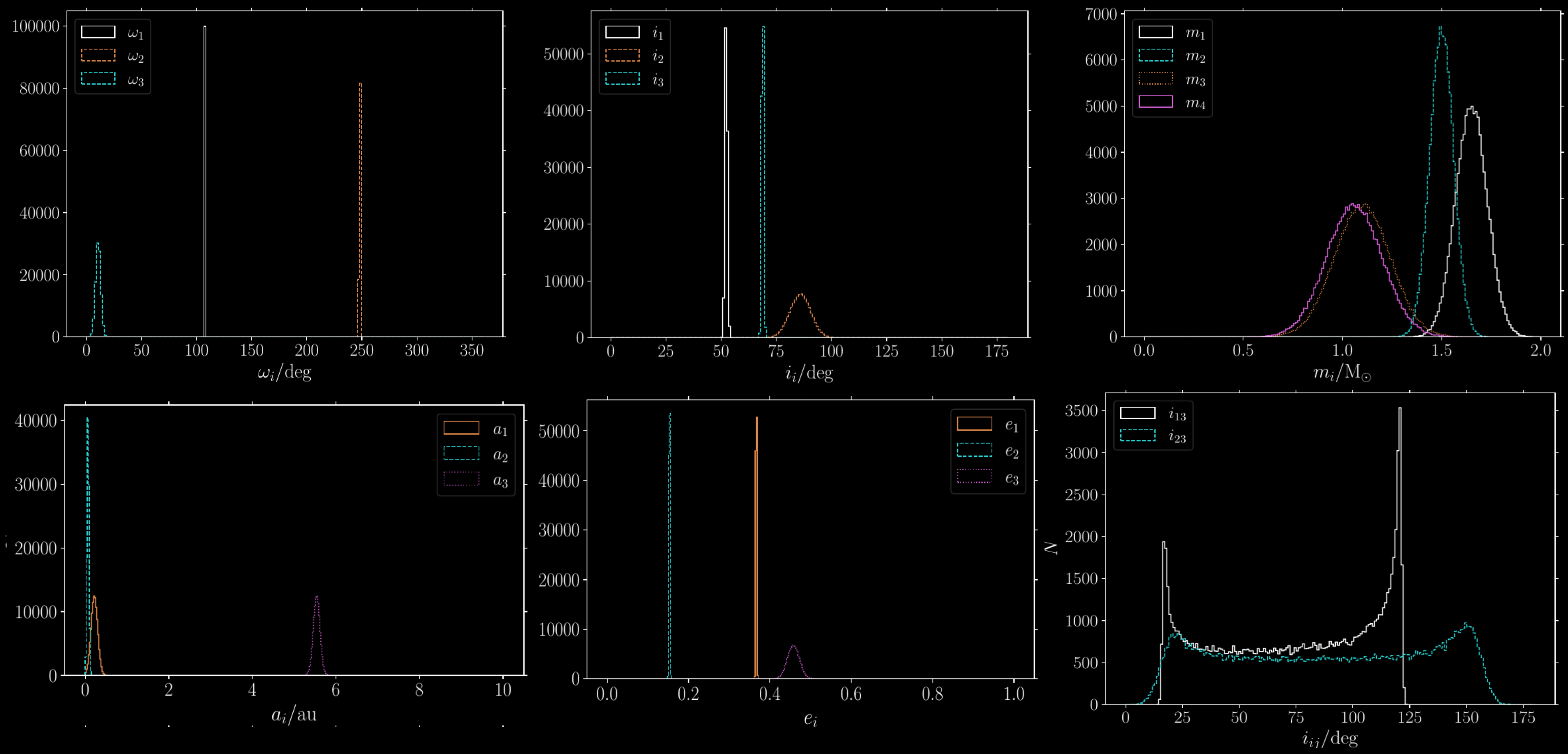
Multiplicity fraction [%]



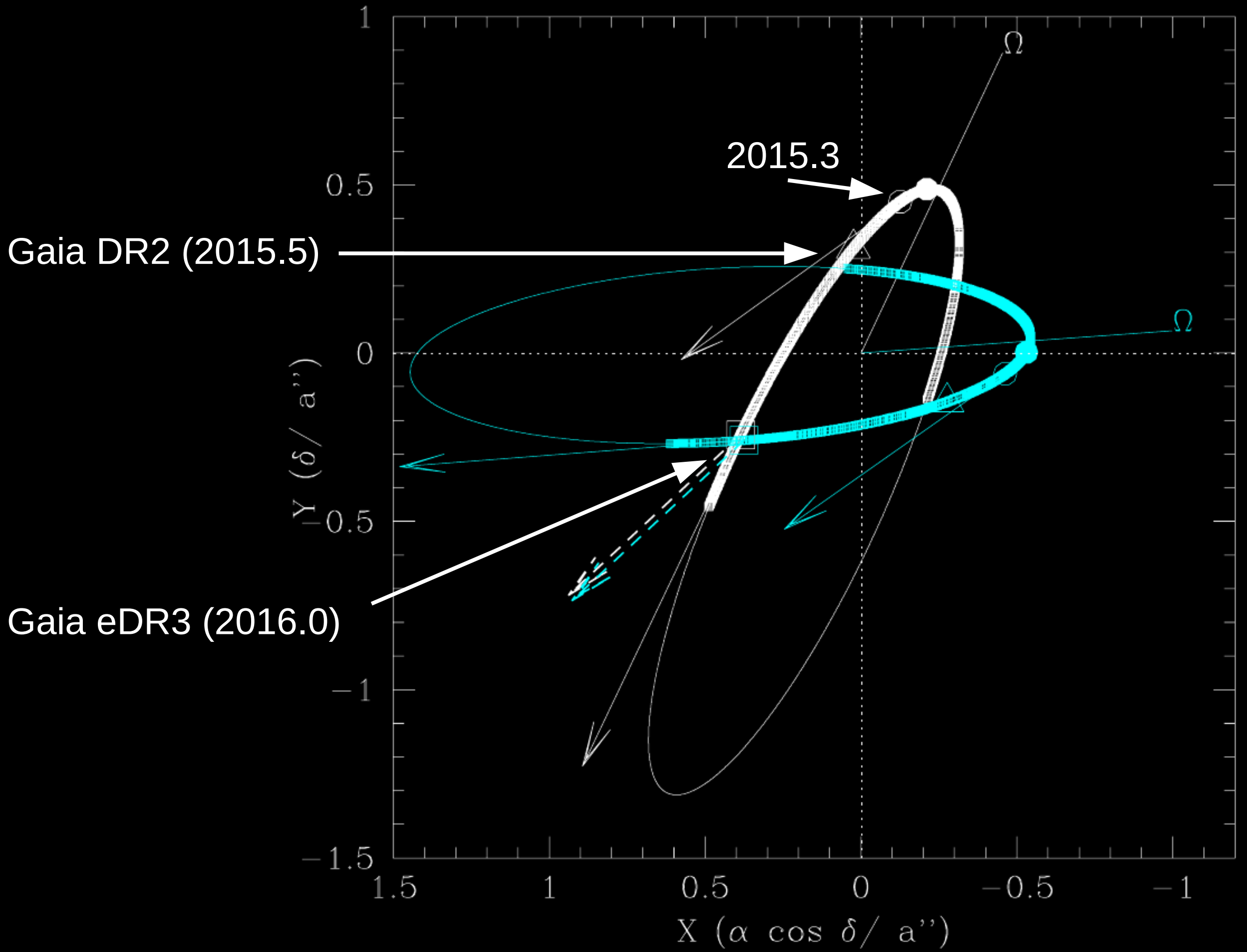
72.3	20.6	5.6	1.5	0.36	Reylé+ (2021)	10 pc sample (339 systems)
60	30	9	1	0.51	Moe & Di Stefano (2017)	25 pc solar-type sample (404 systems)
47	37	13	5	0.78	Furhmann+ (2017)	25 pc solar-type sample
54	33	8	5	0.64	Tokovinin (2014)	67 pc FG dwarf sample
54	34	9	3	0.61	Raghavan+ (2010)	25 pc solar-type sample (454 systems)
57	38	4	1	0.49	Duquennoy & Mayor (1991)	164 systems FG 22 pc
42	46	9	2	0.70	Abt & Levy (1976)	135 bright FG stars with V<5.5

Mean number of companions

Initial conditions for MSE simulations



Constraining the longitude of ascending node with Gaia astrometry

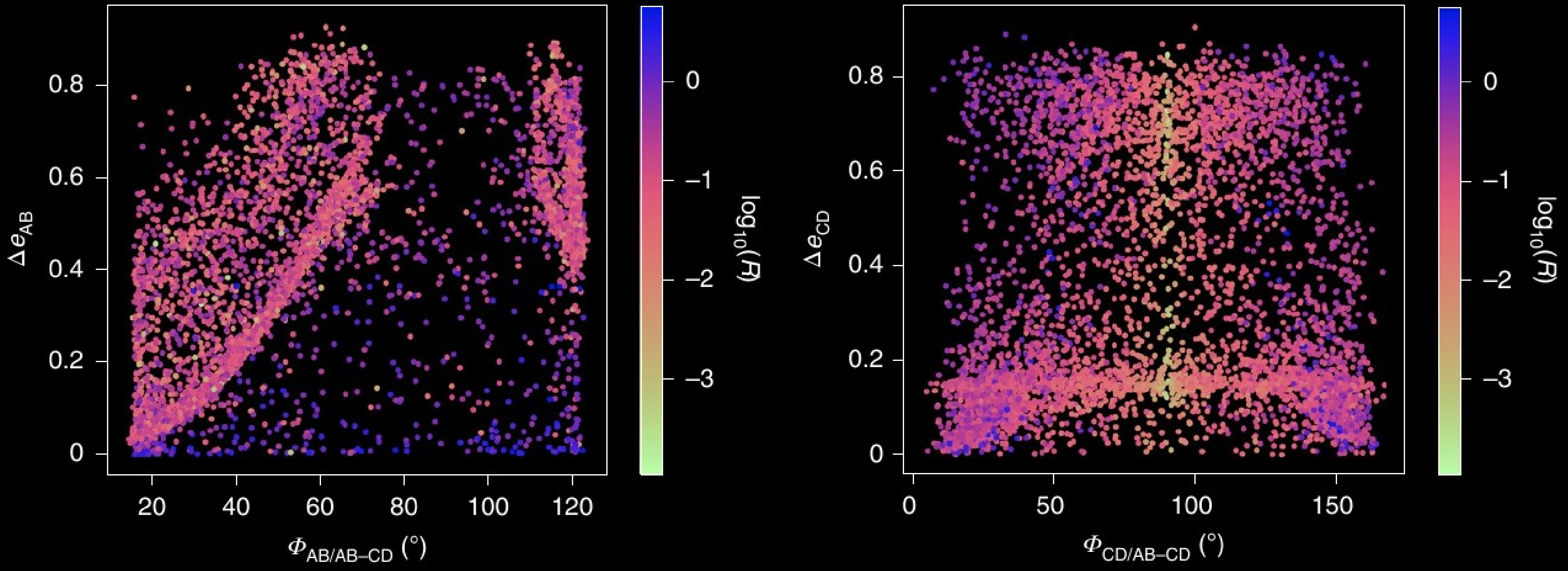


i = 73°
Ω = 333°

i = 107°
Ω = 274°

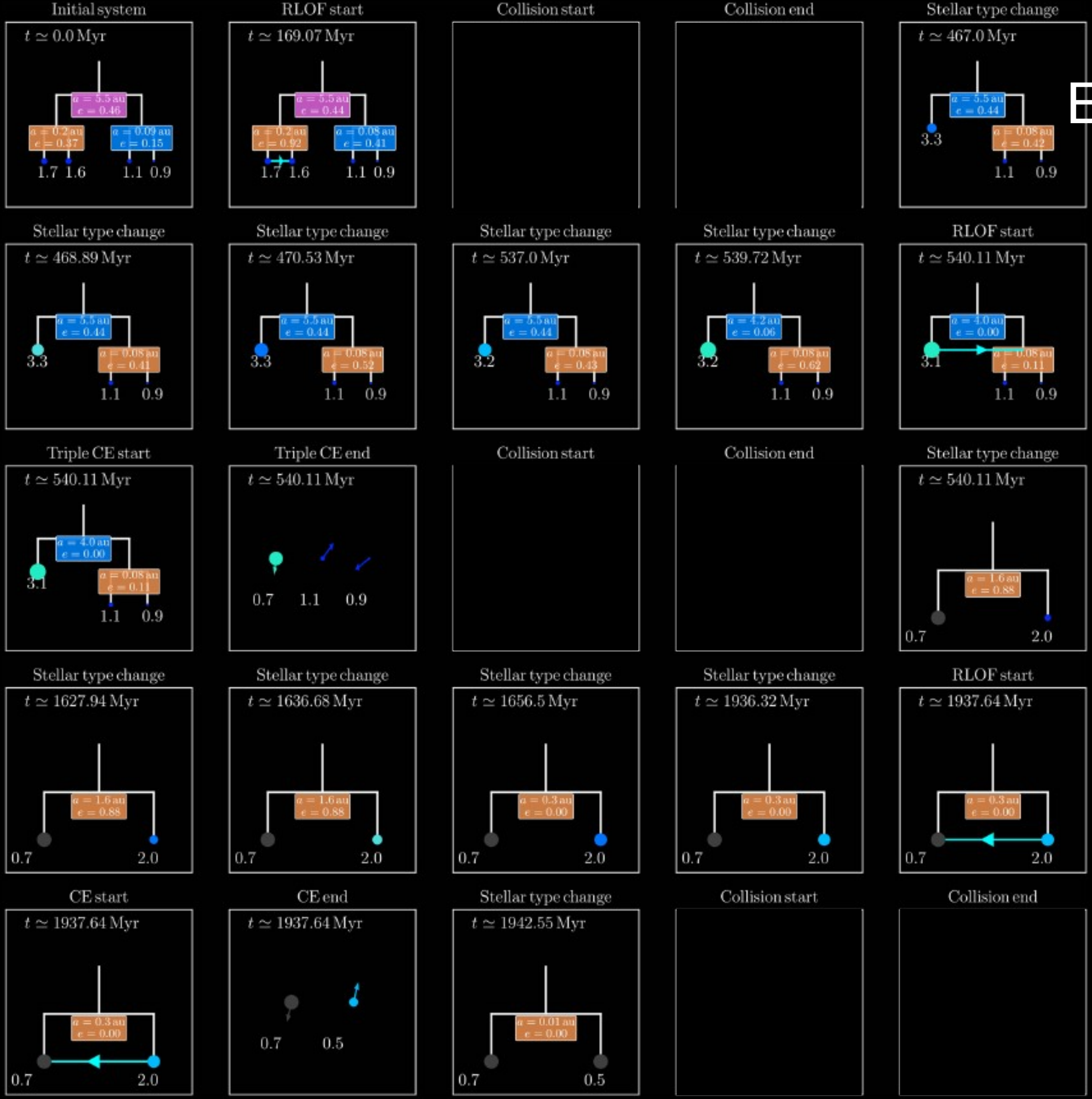
MSE simulations of the evolution of HD 74438

Monte-Carlo methods to sample 10k realizations
Longitude of ascending nodes samples from flat distributions



R: LK timescales ratio for inner-to outer orbit pairs (Hamers 2017)

Example of one realization

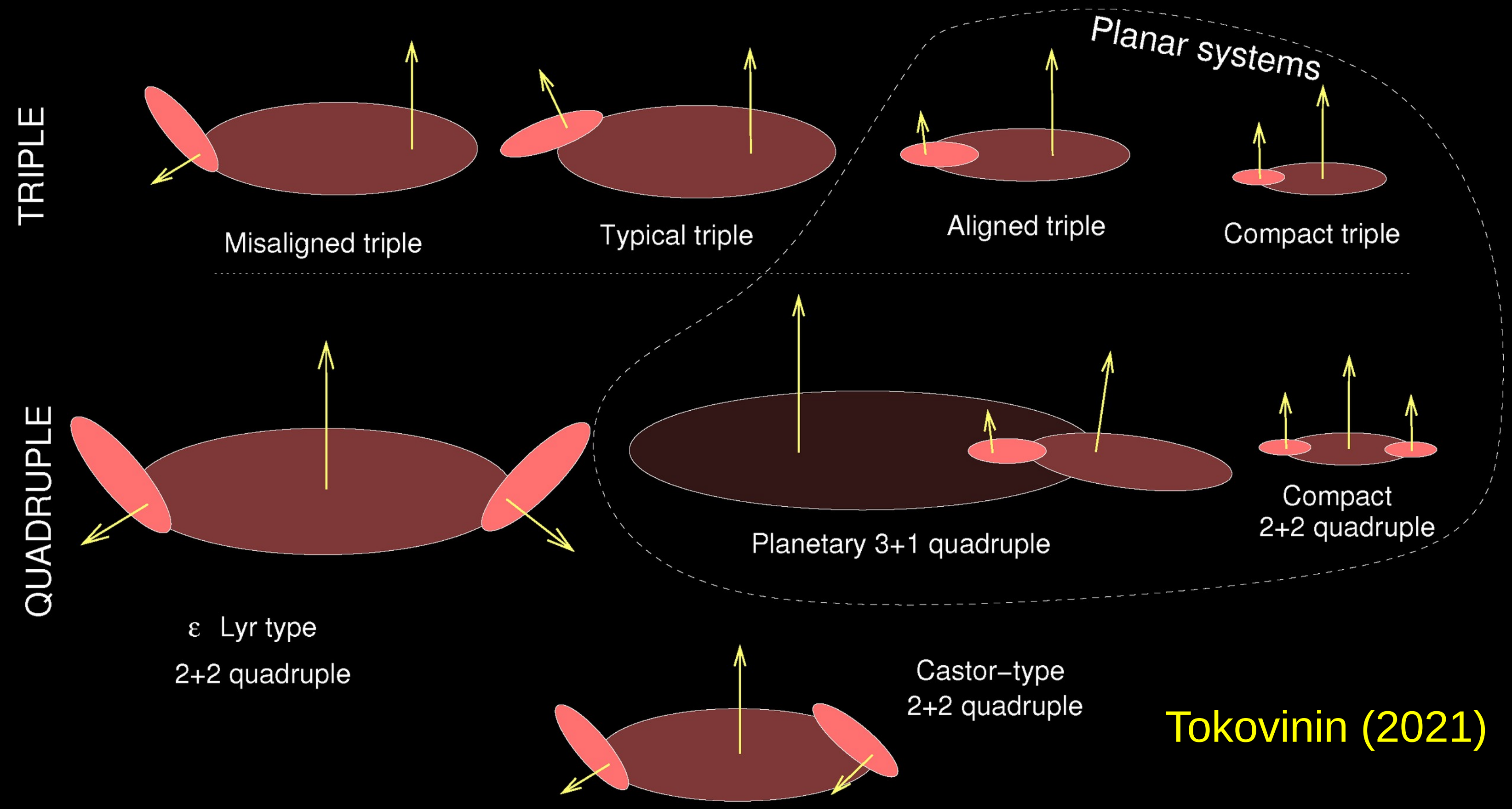


Time

RLOF
Triple RLOF and CE
3 mergers events

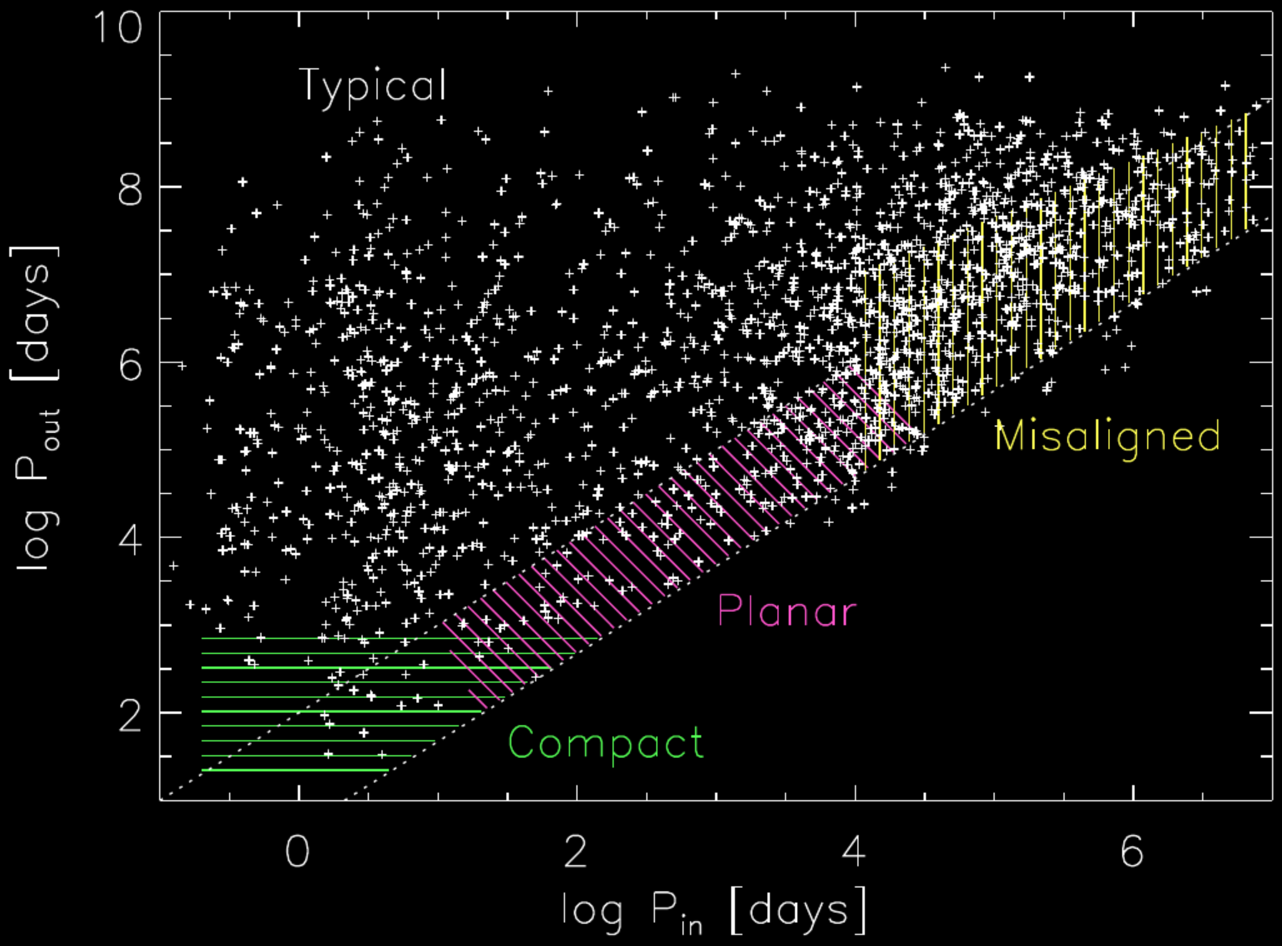
White dwarf with a sub-Chandrasekhar mass of 1.3 $M_\odot$

Architecture of hierarchical stellar systems



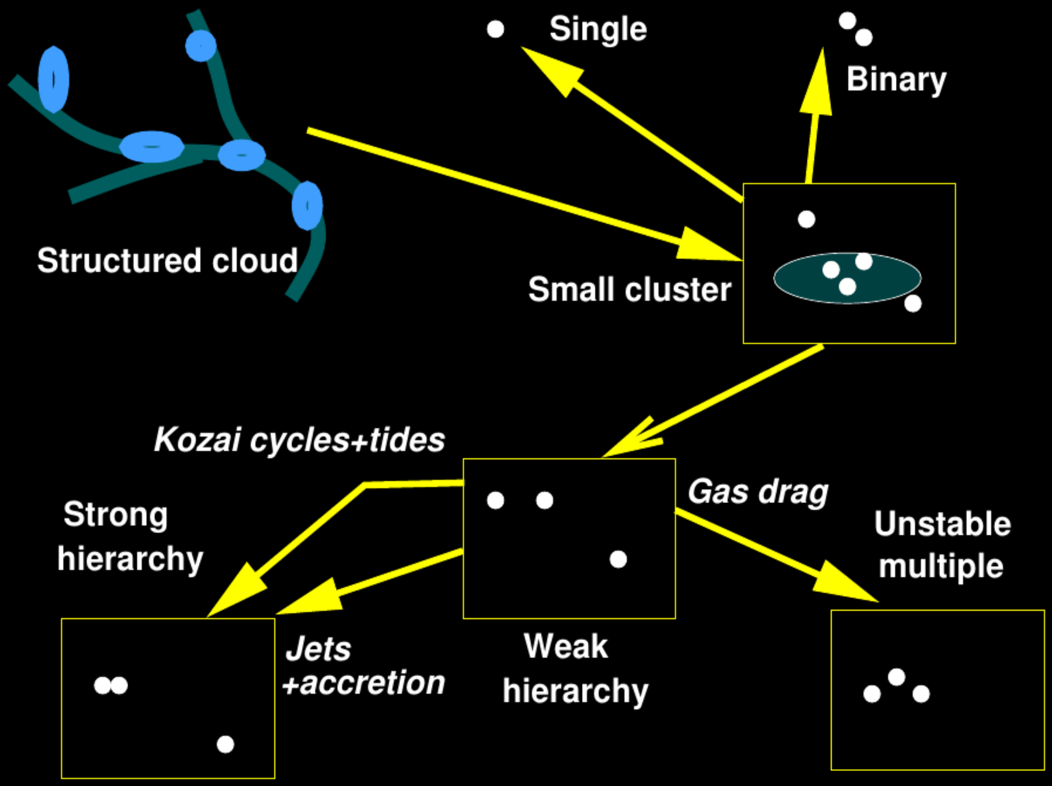
Tokovinin (2021)

Periods of the inner and outer binaries



Tokovinin (2021)

How do stellar systems form?



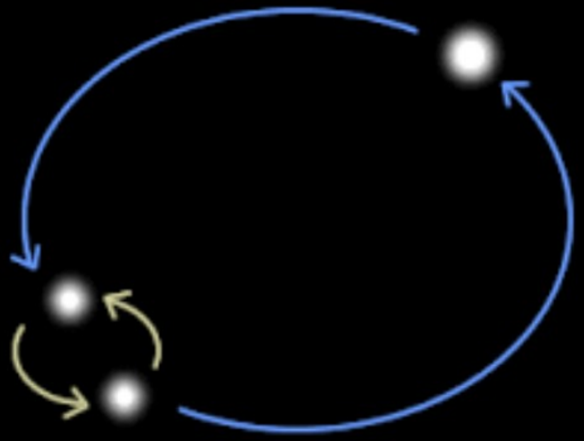
Tokovinin (2014)

Molecular clouds
↓
open clusters
↓
mini-clusters
↓
associations
↓
Mobile groups
↓
Field stars & hypervelocity stars

Introduction: why do we care about stellar multiples?
2. Stellar formation

Core fragmentation
at large scales
(100 – 30 000 au)

Disk fragmentation
at intermediate scales
(0.1 – 100 au)



Dynamical hardening in triple
at small scales
(< 0.1 au)